IL NUOVO CIMENTO Vol. 34 C, N. 5 Suppl. 1 Settembre-Ottobre 2011
DOI 10.1393/ncc/i2011-11001-2

Colloquia: LC10

Antimatter and dark-matter search in space

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(ricevuto il 20 Luglio 2011; pubblicato online il 6 Ottobre 2011)

Summary. — The study of cosmic rays in space has acquired a unique importance in recent years, due to the fact that they are a powerful tool for understanding the mechanisms of the origin of the Universe or the nature of dark matter. Experiments already flown or currently in orbit, conducted on balloons, satellites and ISS, allowed to make huge strides in understanding the mechanisms of production and acceleration of cosmic rays, and have posed new questions to which we hope to answer in the near future.

PACS `96.50.sh` – Interplanetary propagation and effects.
PACS `95.35.+d` – Dark matter (stellar, interstellar, galactic, and cosmological).

1. – Introduction

Cosmic rays are a unique tool to address the problems of the apparent absence of cosmological antimatter, the nature of the dark matter that pervades the Universe and the origin and evolution of matter in our Galaxy. In a Universe created in a state with a quantum number of the vacuum, as the big bang theory requires, the amount of fermions would be equal to the amount of antifermions, and this symmetry between matter and antimatter would persist as the Universe expands and cools. However, there is large evidence of a local asymmetry between matter and antimatter, and no plausible mechanism for a large-scale separation in the early Universe has been formulated.

In a pioneering paper in 1967 [1], Sakharov enunciated the general requirements for the generation of a baryonic asymmetry: there must be interactions that violate the baryon number conservation, the charge conjugation invariance and the CP symmetry, in addition to a departure from thermal equilibrium at some stage in the evolution of the Universe. Such processes are possible in principle via phase transition in the Standard Model, but the GUTs theories are considered more likely sources of the matter-antimatter asymmetry. Unfortunately, there is no direct laboratory evidence that baryon number is violated. The maximum C violation occurs in weak interactions, while neutral kaon is an example of CP violation in the quark sector which has a relative strength, $\sim 10^{-3}$, too small to explain the large matter and antimatter asymmetry. Beyond the SM there are many sources of CP violation.

An extensive search of large antimatter domains in the visible Universe has been performed looking at additional amounts of gammas in the extragalactic diffuse background gamma radiation, to be ascribed to the annihilation of protons and antiprotons at the domain boundaries. The results were largely negative. However, the detection of a rate of antiprotons much higher than expected from interactions of cosmic rays with the interstellar matter, done by the pioneer experiments of R. Golden [2] and E. Bogomolov [3] in 1979, suggested the hypothesis of a flux of antimatter escaped as cosmic rays from a distant galaxy. In the last twenty years a large number of balloon and satellite experiments—focused on antimatter detection—have been performed by the WiZard, BESS, HEAT, PAMELA and AMS Collaborations. The first pioneer results on the antiproton-to-proton ratio have not been confirmed and, up to now, no evidence of the existence of large domains of antimatter appeared.

In the same period, cosmological observations were providing growing evidence that the energy density of the Universe is essentially in form of dark matter and dark energy. The dynamical motions of astronomical objects such as rotation curves of spiral galaxies, the velocity dispersion of individual galaxies in galaxy clusters, the mass of galaxy clusters got by gravitational lensing, the large-scale structure formation from the initial seed perturbations, all necessitate an amount of matter much higher than the quantity the big bang theory allows for baryonic matter. Therefore, there is a clear indication that non-baryonic dark matter is the building block of all the structures in the Universe. On the other side, the positive acceleration of the Universe inferred by the WMAP data suggests a large component of an unknown dark energy.

Current knowledge suggests that the energy budget of the Universe is constituted of baryonic matter (4%), dark matter (23%) and dark energy (73%). The nature of the astronomical dark matter is still unresolved. The dark matter is generally assumed to be a neutral weakly interacting massive particle (WIMP) with a mass in the range between 10's GeV and TeV. Its presence is predicted in several classes of extension of the Standard Model of particle physics. There are many well-motivated particle physics candidates; the most studied are the lightest SUSY particle, the neutralino, and the lightest Kaluza-Klein particle, in the Universal Extra Dimension framework. These particles can annihilate each other giving, through some intermediate annihilation channel, proton-antiproton, electron-positron, neutrino-antineutrino pairs and gammas as final states.

For such reason, antiparticle search in cosmic rays is very prominent, as a powerful tool to detect signals of dark-matter annihilation. The main challenge in this task is the separation of the WIMP signals from the huge astrophysics background originated by interaction of high-energy cosmic rays with the interstellar matter. Looking at distortions and spectral tilts in the energy spectra of these secondary antiparticles is the way to explore.

2. – Antimatter and dark-matter space missions

The old balloon-borne experiments allowed the development of particle physics detection techniques for space and the improvement of new analysis methods. A real discovery chance of antinuclei with $Z \geq 2$ and of possible dark-matter signals needs experiments that explore a wide interval of energy with high statistics, allow a better knowledge of the astrophysics background and monitor continuously and for long periods the solar activity that affects the low-energy spectrum of the cosmic rays. The in-orbit satellite experiments PAMELA, Fermi and AMS-02 constitute the most important effort done in the field up to now. Even long-duration balloon flights, as BESS and ATIC, are giving important contributions.

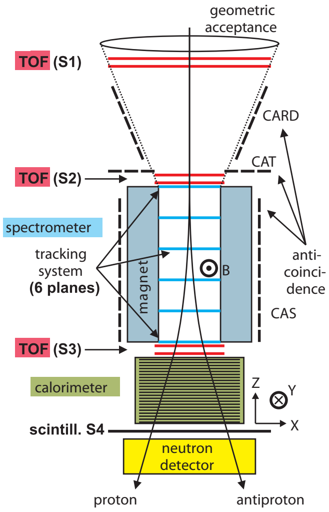

Fig. 1. – General scheme of PAMELA.

2˙1. *PAMELA mission.* – PAMELA—a Payload for Matter-Antimatter Exploration and Light nuclei Astrophysics—is a general-purpose charged-particle detector system, exploring the particle and antiparticle components of the cosmic radiation over an energy range between tens of MeV and many hundreds of GeV. PAMELA was launched in orbit on board the Russian satellite Resurs DK1 the 15th of June 2006 and inserted in a quasi-polar (inclination 70°) low-earth elliptical orbit at an altitude ranging between 350 and 610 km. 16 gigabytes of data are daily transmitted by the satellite telemetry from PAMELA to the Ground Station in Moscow. A magnetic spectrometer for particle electrical charge sign determination and rigidity (momentum/q) measurement is the core of the instrument. An imaging silicon calorimeter, a neutron detector and a thick scintillator allow a separation between electronic and hadronic components of cosmic rays of the order of 10^5 if electrons and positrons are selected. A set of plastic scintillators give the general trigger to the instrument and measure the time of flight of particles crossing the spectrometer. An additional set of plastic scintillators in anticoincidence defines the acceptance of the particles inside the spectrometer. The general scheme of the instrument is shown in fig. 1. Details are reported in ref. [4].

Particle identification in PAMELA is mainly based on the determination of the rigidity measured by the spectrometer and the properties of the energy deposit and interaction topology in the calorimeter. The spillover (protons in the antiproton sample and electrons in the positron sample) limits the rigidity interval in which the measurements can be performed. An important source of background comes from the misidentification of like-charged particles (electrons in the antiproton sample and protons in the positron sample). Electron and positron identification is performed by the matching between the momentum measured by the tracker and the total energy measured in the calorimeter, the starting point and the lateral and longitudinal profiles of the reconstructed shower, the neutron detector response [5].

The antiproton energy spectrum and the antiproton-to-proton flux ratio measured by PAMELA [6] in the energy interval between 60 MeV and 180 GeV are shown in fig. 2,

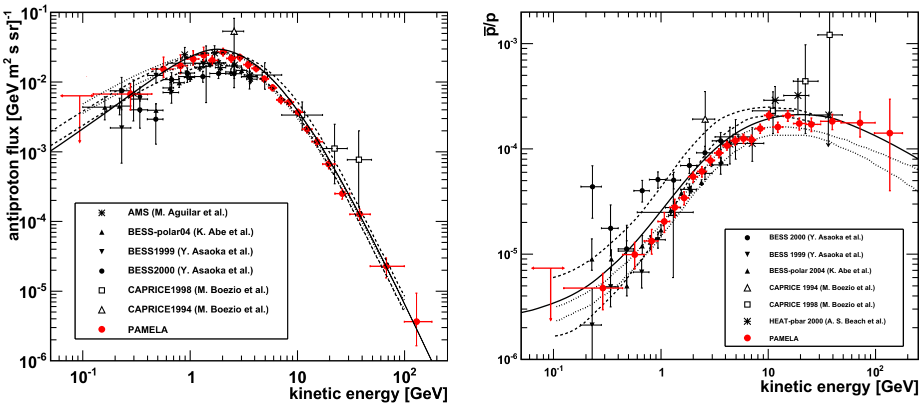

Fig. 2. – PAMELA antiproton flux (left) and antiproton/proton ratio (right) [6] together with data from other experiments and theoretical calculations.

left and right respectively, along with other recent experimental data and theoretical calculations of secondary production of antiprotons during the propagation of cosmic rays in the Galaxy. The results reproduce the expected peak around 2 GeV in the antiproton flux and are in overall agreement with pure secondary creation. However, the precision of the measurements is better than the theoretical previsions, placing strict constraints on parameters relevant for secondary production calculation.

The positron to all electron (*i.e.* electron + positron) ratio measured by the PAMELA experiment [5, 7] in the energy range 1.5–100 GeV is given in fig. 3, together with other recent experimental results and compared with a GALPROP calculation of the astro-

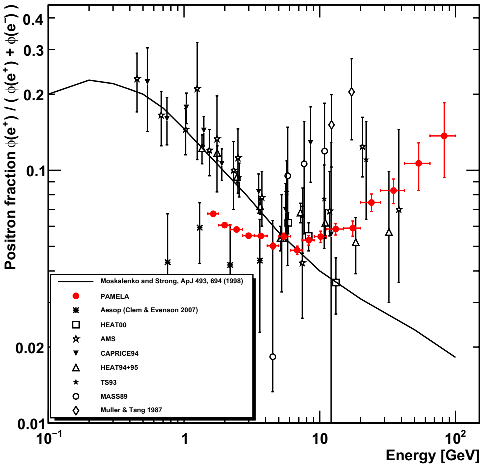

Fig. 3. – PAMELA positron-to–all-electron ratio [7] together with data from other experiments and a GALPROP calculation.

physics background. At low energies, below 5 GeV, the PAMELA results are systematically lower than the data collected during the 1990s; this can be explained by effects of charge-dependent solar modulation. At high energies, above 10 GeV, the data show an increase of the positron fraction with energy, not in agreement with the expected continuous decrease. Many explanations about the origin of this positron excess have been proposed, ranging from purely astrophysical one, like pulsars or few nearby Supernova Remnants (SNR), to the more speculative ones, as annihilation of dark matter, decaying of the lightest superparticle dark matter or even cosmic strings.

The most problematic theoretical challenge posed by the PAMELA results to a dark-matter description 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 direct annihilation in leptonic channels [8] that allows a satisfying fit of the PAMELA data for a wide range of the WIMP masses and overcomes the lack of an antiproton excess, or the introduction of a new dark sector of forces [9]. In [10] it is noted that any signal in the antiproton energy spectrum may be hidden due to incomplete modelling of secondary production and cosmic-ray propagation. Explanations involving Kaluza-Klein (KK) dark matter [11], well reproducing the PAMELA data, have been taken into account. A common difficulty for these descriptions is the necessity of a large boost factor for the annihilation standard rate, of the order of 10^2–10^3.

It is worth to note that the Fermi experiment did not find any perceptible signal of dark matter in the gamma channel so far. Moreover, a peak between 600 and 800 GeV found by the balloon-borne experiment ATIC [12] in the all electron spectrum and explained in terms of dark-matter annihilation has not been confirmed by the all electron Fermi data [13]. However the significant flattening of the Fermi data does not exclude dark-matter scenarios.

Other plausible explanations of the PAMELA data in terms of contributions from nearby and young pulsars—objects well known as particle accelerators—have been formulated. Theoretical models [14, 15] predict that 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 that, in the presence of pulsar huge magnetic field, can evolve in positrons and electrons pairs. These, escaping into the interstellar medium, give a further contribution to the electron and positron components.

The PAMELA positron data can be explained also without invoking a primary component, if a possible inhomogeneity in the distribution of SNRs in our Galaxy is taken into account [16] or if secondary production takes place in the same region where cosmic rays are being accelerated [17-20].

2·2. *AMS-02 mission.* – On May 16th 2011 the AMS-02 instrument was launched on board of the Shuttle and placed outside the International Space Station. AMS-02 is a worldwide collaboration. The detector, shown in fig. 4, has a size of $3 \times 3 \times 3\,\mathrm{m}^3$ and a weight of 7 tons. The main instrument of AMS-02 is a magnetic spectrometer composed of a permanent magnet of neodymium alloy with a magnetic field of 0.125 T and of a tracking system made of 8 microstrip silicon layers, each of $0.8\,\mathrm{m}^2$ and a resolution of $10\,\mu$m in the bending view. The MDR ranges from 0.23 TV for an acceptance of $0.41\,\mathrm{m}^2$ sr to 2.21 TV for an acceptance of $0.01.\mathrm{m}^2$ sr. 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, composed by 4 scintillator planes for a total of 34 crossed scintillator paddles, a

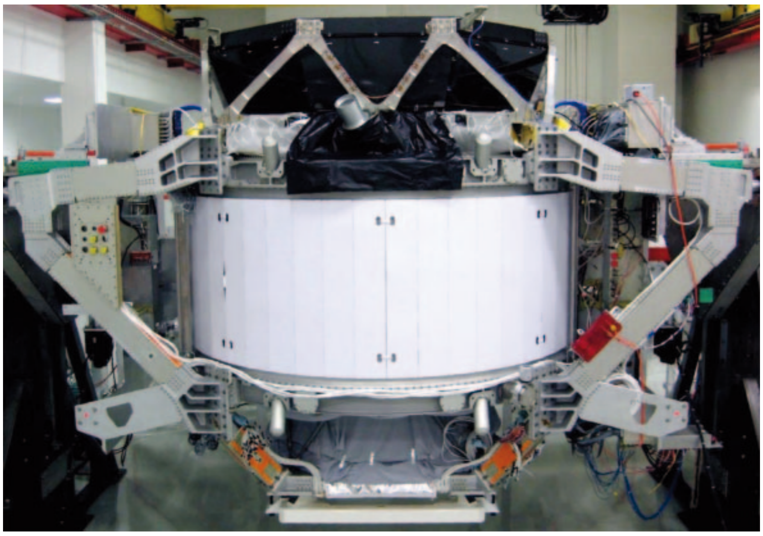

Fig. 4. – A recent photo of the AMS-02 space detector.

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 16 radiation lengths is added to the bottom of the apparatus; it is made of 9 superlayers of lead scintillating fiber sandwiches disposed along X and Y alternately.

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 measurements of cosmic-rays spectra and chemical composition up to 1 TeV. AMS-02 is also a powerful gamma detector. This unique feature of combining searches in different channels—antiprotons, positrons and gammas—could give much higher sensitivity to SUSY DM signals. AMS-02 is expected also to give a crucial answer about the limit in energy of the positron fraction increase found by PAMELA. The search of heavy antinuclei will have a big improvement with the launch of AMS-02, due to its very large acceptance and the foreseen long permanence in space.

3. – Polar balloon flights

Long duration polar flights represent a new interesting opportunity for cosmic-rays research, at a lower 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, with an acceptance of $0.3\,\text{m}^2\,\text{sr}$, was composed by a superconducting solenoid magnet, with 0.8 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/μ rejection. The scientific objectives were the search for antiparticle and antimatter in the low energy region and the precise measurements of various

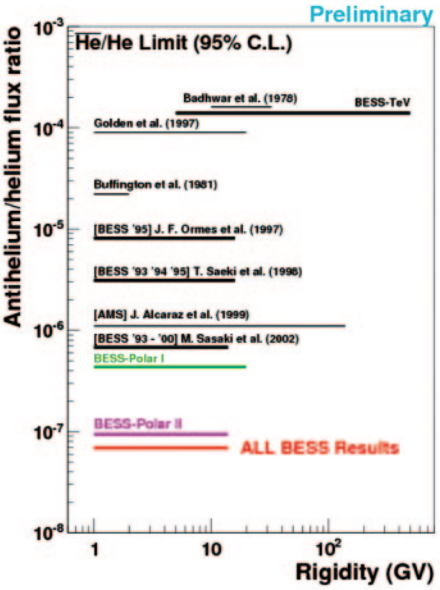

Fig. 5. – Antihelium/helium limit from several experiments.

primary cosmic rays. Roughly 9×10^8 events were recorded. The main results in antip/p ratios [21] are shown in fig. 2.

A real quality improvement on long-duration flights has been done on the 23rd of December 2008, when the BESS Polar II experiment was launched from William Field, McMurdo, in Antarctica. A new magnet was used and all other subsystems were upgraded. The floating time was of 29.5 days with 24.5 days of data taking. Roughly 4.7×10^9 events were recorded. The most important result shown by BESS [22] up to now is a new limit in antihelium-to-helium ratio. Combining all the BESS flight data, a value of 6.9×10^{-8} is obtained, as shown in fig. 5 (preliminary). Promising results on antip/p ratio and on the antideuterium search from the analysis of the collected data are expected.

A very interesting experiment ready to start is GAPS (General Antiparticle Spectrometer [23]), configured as a long-duration balloon-borne experiment that will detect antideuterons in cosmic rays with a background-free method. Antideuterons are expected as possible signature of dark-matter annihilation from antiprotons and antineutrons followed from a fusion of the two nucleons, while astrophysical production of antideuterium at low energy is largely suppressed by kinematical constraints. Antideuterons are degraded in velocity and captured in an active target, resulting in an exotic atom in an excited state. The exotic atom then quickly decays, producing X-rays of precisely defined energies and a correlated pion signature from nuclear annihilation. The method of detection uses a Time-Of-Flight which tags candidate events and particle velocities and planes of pixelated Si(Li) detectors, which serve as the target material and tracking detector. The SI(Li) detectors provide both excellent X-ray energy resolution and good particle tracking. The method has already been successfully tested at KEK accelerator. A prototype of the instrument is planned to fly in 2011.

4. – Conclusions

The search of heavy antimatter and the indirect search of dark matter is now at the highest level by the in-orbit experiments PAMELA, Fermi and AMS-02. The intriguing results of PAMELA on the positron to all electron fraction and the flattening of the all electron energy spectrum seen by Fermi will hopefully find an answer in the next future by the expected AMS-02 results. The long monitoring of the solar activity by PAMELA is giving to theorists the possibility to tune their models on solar modulation, allowing the disentanglement of possible signals of dark matter even in the low-energy part of the antiparticle spectra. Evidences of cosmological antimatter are expected from AMS-02.

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