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The BALLOON-borne and PAMELA experiments for the study of the antimatter component in cosmic rays

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Abstract

The PAMELA experiment is based on a satellite-borne equipment actually in the final integration phase. It will be installed on board of the Russian satellite Resurs DK1 and launched in a quasi-polar orbit from the Baikonur cosmodrom at the beginning of next year. PAMELA will measure the antiproton and positron fluxes in cosmic rays with high statistics and in a large energy range (80 MeV–190 GeV for antiprotons and 50 MeV–270 GeV for positrons), extending to never investigated energies the measurements of several balloon borne experiments performed by the same PAMELA collaboration in last decade. This will make achievable sensitive tests of cosmic ray propagation models in the Galaxy and the search, in an energy range never investigated before, of possible structures in the fluxes. These structures, related to the presence of primary antiparticle sources, could be signals of "new physics", connected with open problems like dark matter existence and matter/antimatter symmetry in the Universe. The detector consists of a very precise magnetic spectrometer, several scintillation counter hodoscopes to measure the energy losses and times of flight, and a high granularity and deep Si–W calorimeter, augmented by a very compact transition radiation detector and a He3 neutron detector hodoscope, and protected around and on the top by an anticoincidence system.

1. Introduction

The direct detection of the galactic cosmic rays (GCR) allows a detailed study of their origin, their propagation in space and their interaction with the environment. Due to the high value of their spectral index, beyond 1 PeV their study is too indirect and affected by uncertainties because they can only be observed by the air shower (EAS) they produce in the atmosphere.

The most important items of the study of CR can be listed according to the energy that can be reached in their direct detection in space:

(1) elemental composition beyond the iron group up to the actinides, at the 'bulk' of the spectrum ($\leqslant$ 1 GeV/nucleon), given their tiny flux;
(2) energy spectra of light nuclei and isotopes, up to a few tens GeV/nucleon;
(3) energy spectra of antiparticles and search for antinuclei, up to a few hundred GeV;
(4) elemental composition of GCR at the knee, up to a few hundred TeV/particle.

These items are all connected to the nuclear and particle physics, above all the third one, to whom will be dedicated the subsequent sections.

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2. Antimatter in the universe: to be or not to be?

The antiparticle energy spectra and the search for antinuclei are among the most important items in the study of cosmic rays, where the interests of the astrophysics and particle physics converge: (i) for what concerns the astrophysics it poses the basic question of the matter–antimatter symmetry of the Universe composition; (ii) for particle physics the study of the antiparticle energy spectra is suitable for giving signals of the so called new physics, by observing possible distortions of their spectra.

After the formulation by Dirac of the hypothesis of the antielectron in 1928, and its discovery in cosmic rays by Anderson in 1932 the cosmological theories were constructed on the basis that perfect symmetry between particles and antiparticles in the fundamental laws of nature had no reason to be put in doubt. Starting from the fluctuations in the matter–antimatter mixture in the primordial Universe these cosmologies could neither justify the formation of 'all matter' astronomical objects greater than a tiny fraction (less than 10^{-30}) of the Sun nor avoid a huge 'annihilation catastrophe', resulting in a discouraging small ($<10^{-18}$) baryon to photon ratio in the Universe, well far away from the observed 10^{-9}.

After more than 30 years of conjectures, the discovery of the CP violation in 1964 allowed A. Sacharov to formulate the famous three hypotheses allowing to justify either an "all matter Universe", or a Universe where matter and antimatter are separated in large domains, originated by CP violation in small regions of the primordial matter and expanded to astronomical dimensions by the inflation mechanism.

Observations of the electromagnetic spectra allow only to put stringent limits on the existence of antimatter at astronomical level in our group of galaxies ($<10^{-8}$ of the Universe volume). We can indeed only relay on the direct observations.

The most straightforward is the observation of an antinucleus that could not be formed neither by collision of particles (as it could be antiHe3), nor to be a primordial product of the first phases of the Universe evolution (as it could be He4). It would be a perfect signature, with no background. However it is not possible to formulate any prevision, except that the time for the diffusion of a low energy antinucleus up to our region of the Universe could be longer than the life of the Universe. This requires that the hunting for antinuclei will be pushed at high energies, what also could allow to the antinucleus to win the galactic wind and penetrate the Galaxy.

The possible 'all antimatter' domains should leak also positrons and antiprotons, and give signals in the spectrum of these antiparticles registered near the Earth.

A possible signal of extragalactic positrons would be flooded by the positrons produced by many other processes, due to their low mass. Electrons and positrons are important for studying these processes from an astrophysics point of view. It must however be underlined that the distorsion of their spectra could give a signal of the so called 'new physics', for example by the massive annihilation of heavy neutralinos.

The flux of antiprotons secondarily produced on the interstellar matter can be estimated relatively well, up to a factor two, depending by the model assumed for the Galaxy. When normalized to the proton flux, this background reaches its maximum at about 10 GeV, decreasing afterward and leaving the possibility of emerging to a possible extragalactic signal. Therefore also for antiprotons it is very important to push the measurement of their flux up to very high energies, at least a few hundred GeV. It must here underlined that at high energy it is also enhanced the possibility of detecting distorsions of the antiproton spectrum due to the annihilation of the new particles expected by supersymmetric models and candidates for explaining the dark matter contribution to the mass of the Universe.

The present experimental situation for the antiproton component is founded on the results obtained by many balloon borne experiments in the last three decades (for a complete list of references see [1]). The main reasons are that the fluxes of antiparticles are low and the instruments dedicated to the measurement of their fluxes cannot be light. The only in orbit experiment dedicated to this research (WIZARD [2] for the ASTROMAG facility [3] on board of the FREEDOM Space Station) designed in the 80s was never realized for the cancellation of the Station.

Most of the above quoted antiproton experiments gave also a limit for the presence of antihelium nuclei. No antihelium nuclei have until been now found.

3. Means of flight

3.1. Balloon borne experiments: limits of the techniques

The balloons suitable for performing antiparticle experiments are the biggest ones, up to 3 million cubic meters when fully deployed, because they must bring at 40 km floating very heavy instruments, up to 3 t in mass.

They are open at bottom, such as a mongolfier, and lose helium gas when the external temperature falls at sunset. To recover altitude for continuing the experiment for the following day it must be discharged a mass (“ballast”) of some percent of the total mass, i.e. more than 10% of the instrument mass. This is conflicting with the need of maximizing the masses allocated to the instrument and to the batteries supplying the electric power, and in most of the cases the flight must be terminated after the first day of data taking. Furthermore the temperature profile of the atmosphere, after a fast diminishing from the ground up to about 20–25 km, keeps rising again up to a maximum at about 40 km of altitude; afterwards it keeps decreasing again. Since at the decrease of the external temperature the balloon volume shrinks, its maximum floating altitude cannot be higher than about 40 km. At this altitude the residual atmosphere on top of the balloon is not negligible, about 4 g/cm^2. Already at a few tens GeV, the antiproton flux produced by the primary CR on this residual atmosphere overcomes the antiproton flux produced by the primary CR in the galactic volume. At higher energies the error in the correction become too large to obtain significant results.

In the last decade several long duration balloon flights (LDB), floating for several days (up to 20) at high altitude, were performed. They also use ‘open’ balloons, but the loss of helium is substantially reduced by flying them at very high latitudes, near the poles, during the local illumination period (summer in Arctica and winter in Antarctica) so that the needed “ballast” can be minimized. However, the maximum mass of their payload at 40 km of altitude does not exceed 1 t. This is a too low mass for an instrument for measuring the antimatter component at high energies. Only the BESS instrument, dedicated to the high statistics measurements of the antimatter component at low energies could be improved [4] for planning LDB flights in Antarctica in the next future.

The ultra long duration balloon flights (around 100 days) in program for the next future will use ‘closed’ balloons, i.e. balloons that are thicker and heavier, do not lose helium gas and can withstand a difference of pressure between the helium gas inside and the air outside. They can fly relatively light instruments, less of 1 t in mass. Therefore they hardly will be used for antiparticle measurements in next future.

3.2. Satellite borne experiments: the technical and ‘political’ difficulties

To plan and perform experiments in space by satellite borne instruments is not an easy task, and not only for economical reasons. The techniques to be used are not simple and the physicists must have recourse to the help of a very expensive industry for the preparation of the instrumentation. Furthermore, in general, the spacecraft, the launch vehicle and the lunch operations are much more expensive than the instrument, and exceed the budgets that particle physics and nuclear physics teams are used to handle.

Finally the access to space is increasingly interesting for many other fields of the human activities, and the research on the field of cosmic rays, and of the study of its antimatter component in particular, must compete for resources with many other scientific and social investigations.

In conclusion, also when the cost ‘per datum’ is much less than that for balloon borne experiments, it appears in one single experiment that aspires to collect a large number of data, what implies a heavy technical, organizational and ‘political’ activity for many years of a large team, and with a highly risky result. This is the main reason why most of the teams working in the field of high energy cosmic rays have not enough energy and initial resources to move from ballooning to satellite borne experiments.

4. The antiparticle component: predicitions, and the need of a new generation of observations

In the present measurements the error on the ratio of the antiproton to proton fluxes beyond 10 GeV is too large for obtaining any indication on the trend at higher energies. The trend of this ratio should be constant if the antiproton flux from antiproton proton pairs produced by exotic sources (such as neutralinos annihilations, or mini black holes evaporation) prevails on the antiproton flux secondarily produced in the interstellar matter. It should be instead increasing if the flux of antiprotons coming from antimatter at astronomical scale and entering the Galaxy would prevail. To obtain a significant indication of the trend the measurements of the antiproton/proton ratio should be extended beyond 100 GeV.

Exotic sources of antiprotons could also give a signal of their presence at less than 1 GeV, well below the kinematical threshold for the production of antiproton proton pair in the interstellar matter. This is the approach chosen by the BESS collaboration to afford the problem. Their instrument has been flown several times in last decade. The work of the BESS collaboration will go on with an improved instrument with LDB flights in the Antarctica. Its scientific program is the subject of a dedicated report to this same conference [5].

In the seventies the beginning of the development of the Shuttle vehicle gave to NASA the opportunity of planning a number of observatories (CGRO, AXAF, HST, SIRFT) in orbit around the Earth for assuring a permanent and simultaneous observation of the whole electromagnetic spectrum [6]. For the CR were planned [7] the advanced composition explorer (ACE) for the observation of the low energy cosmic rays (up to a few GeV), launched (in 1999) far away from the influence of the terrestrial magnetic field, and a superconducting magnet facility (ASTROMAG [3]) for the direct detection of high energy cosmic rays. Because of its mass, complexity and serviceability this facility had to be installed on board of the "FREEDOM" space station planned in the meantime.

For the ASTROMAG facility three experiments were selected for affording the most fundamental items mentioned in the introduction: SCINATT-MAGIC [8] for studying the elemental composition at the knee, LISA [9] dedicated to the measurement of the elemental and isotopic energy spectra, and WIZARD [2] dedicated to the measurement of the particle and antiparticle energy spectra and hunting for antinuclei.

The WIZARD collaboration began to work from the very beginning by performing balloon experiments, also conceived for testing the techniques proposed for the experiment in orbit. When the FREEDOM Space Station was unexpectedly cancelled [1] the WIZARD collaboration did not disband and went on working toward the same physics goals either by ballooning or looking for any good occasion for continuing its research in orbit. Two years later, by collaborating with a Russian group of the MEPHI institute in Moscow, it was formulated a common research program, complementing the balloon experimental activity, with low energy CR research on board of satellites [10,11], of the MIR space station [12] and of the ISS [13,14]. The main goal of this program was to perform the study of the antimatter component up to much higher energies, beyond 100 GeV, and from the very beginning it was designed a dedicated satellite borne experiment, nicknamed PAMELA [15].

A few years later also a collaboration formed by many institutions coming from High Energy Physics, following the experimental approach of the PAMELA experiment, afforded the enterprise of constructing a very large acceptance magnetic spectrometer dedicated to the study of the

[1] The cancellation of the FREEDOM Space Station also caused the cancellation of the Hevy Nuclei Collector (HNC) for the study of the actinides mentioned in the introduction, as well the possibility of observing UHECR by the Fly-Eye technique, already in the 1982 NASA plan [7].

antimatter component of CR. After the precursor flight of a simplified prototype on board of the Shuttle the collaboration afforded the realization of a superconducting spectrometer, equipped by several complementary detectors for a robust identification of the measured particles [16].

The PAMELA and AMS instruments represent a long waited new generation of experiments dedicated to the antimatter research at high energy in cosmic rays, and complement the LDB flight program of BESS at lower energies.

The AMS instrument is described in the dedicated talk at this same conference [17] so that I will concentrate on the description of the PAMELA spectrometer and on its expected performance.

5. The PAMELA instrument, its performance and its measurement program

The PAMELA instrument consists of (i) a magnetic spectrometer constituted by 5 permanent magnets interleaving 6 planes of double sided double metallization microstrip silicon sensors, (ii) a very compact, high-granularity (0.24 cm pitch) and deep (16Xo) imaging calorimeter, constituted by 21 tungsten absorbers interleaving 44 planes of microstrip silicon sensors, (iii) a compact TRD on top of the magnetic spectrometer consisting of 18 layers of miniaturized gas tubes and 10 carbon fibre radiators, (iv) a set of three double layers of scintillation counter hodoscopes for supplying the trigger and three ToF measurements, (v) a set of scintillation counters in anticoincidence for protecting the spectrometer region, (vi) a thick penetration scintillation counter on the bottom, followed by (vii) a neutron counter constituted by 36 He^3 tubes.

All the detectors has been tested on particle beams at CERN, either in 'self standing' configuration or assembled together in the final configuration.

The magnetic system provides a bipolar field nearly constant in the whole useful volume of 0.4 T. The silicon tracker reconstructs each point with a resolution of 4 μm in the bending view giving a MDR of 740 GV.

The imaging calorimeter identifies e.m. shower at the level of 10^{-4} contamination, with a resolution $12\%/E^{1/2} + 2\%$ for central straight tracks. In self triggering mode the GF is 470 cm^2 sr allowing the measuring of the electron flux beyond the MDR of the magnetic spectrometer, with useful statistics up to 2 TeV.

The main parameters of the PAMELA instrument are:

+++ acceptance (GF) 20.5 cm^2 sr;
+++ volume $120\times40\times45$ cm^2;
+++ mass 470 kg;
+++ electric power consumption 360 W.

In three years of operation in orbit the PAMELA experiment will measure:

- antiproton flux from 80 MeV to 190 GeV (present limits 0.4–50 GeV);
- positron flux from 50 MeV to 270 GeV (present limits 0.7–30 GeV);
- limit on antihelium to helium ratio (at 90% CL) $\sim6\times10^{-8}$ (present limit 0.7×10^{-6});
- electron flux from 50 MeV to 2 TeV;
- proton flux from 80 MeV to 700 GeV;
- light nuclei flux (up to oxygen) from 100 MeV/n to 200 GeV/n;
- continuous monitoring of cosmic ray modulation;
- continuous monitoring of fluxes and energy spectra of solar cosmic rays.

The expected performance of the PAMELA instrument for the two most important physics channels, the measurement of the antiproton and positron fluxes, are reported in Fig. 1.

As an example in the figures is reported (thin line) the possible contribution that the annihilation of the heavy neutralinos foreseen in the MSSM of the GUT theories could give to this channels. The expectations for the rate collected by PAMELA in three years are reported as small squares for this attractive hypothesis.

The flight model of the PAMELA instrument is presently assembled in Roma Tor Vergata university. After calibration at CERN SPS it will be sent this autumn to TsSKB-Progress in Samara (Russia) to be integrated on board of the RESURS-DK1 satellite. The launch is scheduled for

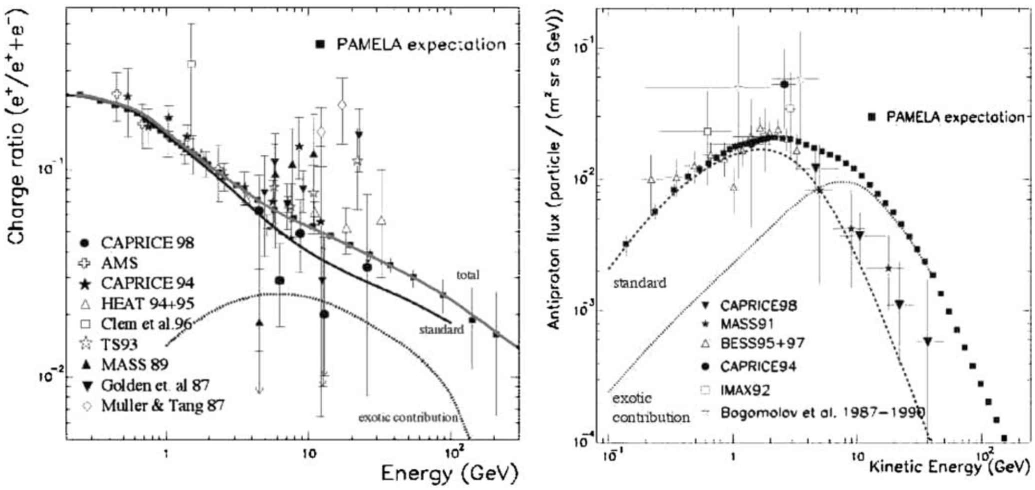

Fig. 1. Expected performance of the PAMELA instrument (small squares) in 3 years of operation, compared with the present experimental situation and the possible contribution from the annihilation of the heavy neutralinos foreseen in the MSSM of the GUT theories (thin line).

the beginning of 2004 from Baikonur cosmodrom by a Soyuz-TM rocket. PAMELA will be placed on an elliptic orbit at altitude 300–600 km and an inclination of 70.4 degrees for a mission lasting at least 3 years.

References

[1] P. Picozza, A. Morselli, astro-ph/0211286 (2002).
[2] P. Spillantini et al., Il Nuovo Cimento 103B (1989) 625.
[3] Astromag Definition Team: The Particle Astrophysics Magnet Facility ASTROMAG, NASA report, May 1988.
[4] A. Yamamoto et al., ICRC (2001) 2135, Hamburg.
[5] M. Nozaki, these proceedings. doi:10.1016/j.nimb.2003.08.005.
[6] Committee on Space Astronomy and Astrophysics: A Strategy for Space Astronomy and Astrophysics for the 1980s, National Academy of Science report, 1979.
[7] Cosmic Ray Program Working Group: Cosmic Ray Program for the 1980s, NASA report, August 1982.
[8] T.A. Parnell et al., Spectra, Composition and Interactions of Nuclei above 10 TeV, NASA MSFC, November 1988.
[9] J.F. Ormes et al., A Large Isotope Spectrometer for Astromag, NASA GSFC, November 1988.
[10] A. Balakin et al., Astrop. Physics 8 (1997) 109;
V. Bidoli et al., ApJ. Suppl. Series 132 (2001) 365;
A. Balakin et al., J. of Geoph. Res. Space Physics, 2002, in press.
[11] M. Casolino et al., ICRC, 5 (1999) 136, Salt Lake City;
M.Casolino et al., ICRC (2001) 2314, Hamburg.
[12] V. Bidoli et al., Adv. Space Res. 25 (2000);
S. Avdeev et al., ICRC (2001) 1745, Hamburg.
[13] S. Avdeev et al., ICRC (2001) 2290, Hamburg.
[14] L. Narici et al., ICRC (2001) 2322, Hamburg.
[15] O. Adriani et al., ICRC 3 (1995) 591, Rome;
O. Adriani et al., NIM A478 (2002) 114.
[16] R. Battiston et al., ICRC (2001) 2192, Hamburg.
[17] C. Lechanoine-Leduc, these proceedings. doi:10.1016/S0168-583X(03)01774-9.