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Antimatter and dark matter: lessons from ballooning.

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Abstract. The balloon measurements done by Victor Hess near Vienna in 1907 can be considered the birth of the Astroparticle physics. Until the advent of accelerators at the beginning of the years 50's the study of the cosmic rays was the base for the most important discovers in particle physics. In the late 70's the detection of antiprotons from space opened new horizons to the research of primary antimatter and signals of dark matter by balloon-borne experiments using the technique developed for accelerator physics. Long Duration Flights in ARTICA and ANTARTICA will permit to overcome the limits of low statistics that limited the validity of these experiments in the study of fundamental physics.

Key words. Antimatter, Dark Matter, Balloon-borne Experiments

1. Introduction

Particle Physics born and developed for many years studying cosmic rays. Positrons, muons, pions and strange particles were discovered detecting directly cosmic rays or products of their interaction with matter targets. In the early 50's with the advent of the particle accelerators the cosmic rays scientific community splitted up in two groups; the particle physicists joined the accelerators while the astrophysicists focused their efforts on the mechanisms of production, acceleration and transport of the cosmic rays. A new turning-point happened with the first historical discovery of antiprotons on the top of the atmosphere by the balloon-borne experiments that Robert Golden and Edward Bogomolov carried out in 1979 (Golden et al. 1979; Bogomolov et al. 1979). They measured a rate of antiprotons much higher than expected from interactions of cosmic rays with the interstellar matter (fig. 1). This event could be considered the return to space of particle physics after more than twenty years. Straightaway various ideas of theoretical interpretation were developed, as primary antimatter coming from antimatter domains in a baryonic symmetric Universe, evaporation for Hawking effect of primordial mini black holes, exotic particles annihilation. In the same years the results of the positron/electron ratio measurements were somewhat similar, with experiments giving an too high flux of positrons at energies higher than 10 GeV, explained with some exotic productions. Many other balloon-borne experiments followed these pioneeristic ones, performed using novel techniques developed for accelerator physics mainly by the WiZard, HEAT and BESS collaborations (Table 1).

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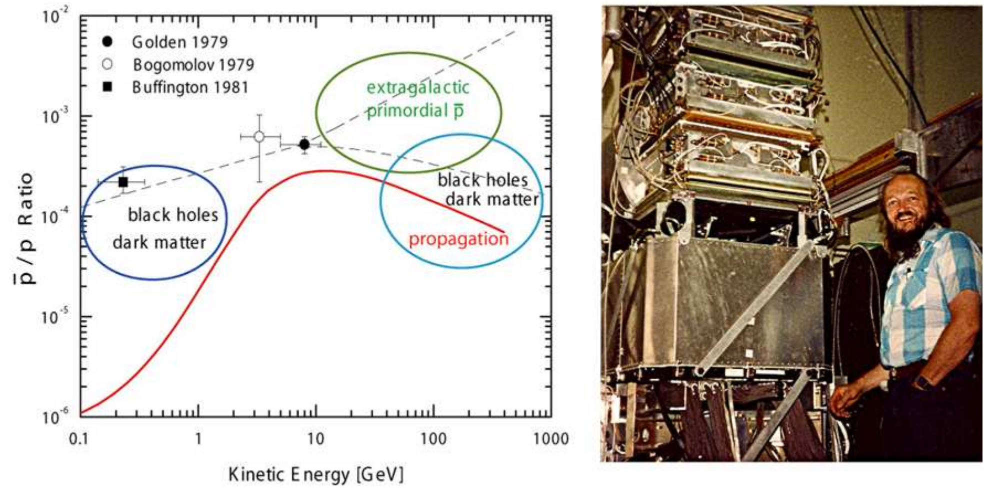

Fig. 1. The first historical measurements on galactic antiprotons. On the right, R. Golden and the MASS instrument.

Table 1. Antimatter and Dark Matter in Cosmic Rays.

1979	First Observation (Golden et al.)
1979	Russian PM (Bogomolov et al.)
1981	Excess reported (Buffington et al.)
1987	LEAP, PBAR (upper limits)
1989	MASS89
1991	MASS91
1993	TS93, BESS
1994	CAPRICE94, HEAT94
1997	BESS
1998	CAPRICE98, AMS01
1999	BESS
2000	HEAT-pbar, BESS
2004	BESS Polar I
2007	BESS Polar II

2. The Balloon Experiment

WIZARD

The WiZard flights MASS 89, MASS 91, TS93, CAPRICE94, CAPRICE98 were a joint effort of USA, Italy, Germany and Sweden collaborators. The core of the instruments was a magnetic spectrometer composed by a superconducting magnet and a tracking system made up of wires and drift chambers. The spectrometer defined the sign of the electrical charge and measured the ratio between the momentum and the electrical charge absolute value. A set of plastic scintillators placed above and under the magnet gave the trigger of the event and provided multiple dE/dx measurements in order to determine the module of the particle electrical charge. In addition, it measured the time of flight of the particles crossing the instrument, providing the determination of their nature up to some GeV/c and the identification of the particles coming from the bottom. The separation between the leptonic and hadronic components was assured by two detectors, an imaging calorimeter and a TRD or Cerenkov. In MASS 89 and 91 the calorimeter was composed of straw-tubes planes, in TS93 and CAPRICE's flights of silicon ministrip layers interleaved with tungsten planes. The second detector was a GAS Cerenkov in the first two flights, a TRD in TS93, a RICH solid Cerenkov and a Gas RICH Cerenkov in the CAPRICE 94 and 98, respectively. The launches were made from Canada Prinz Albert and Lynn Lake sites for the study of the low energy part of the cosmic ray spectrum and from Fort Summer in New Mexico, USA, for the exploration of the high part of the spec-

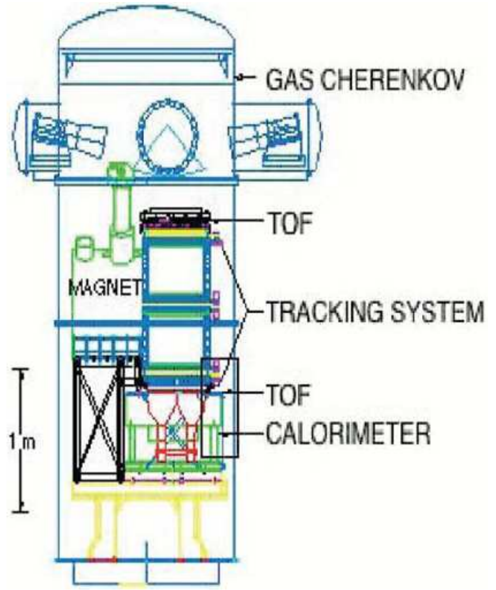

Fig. 2. Mass: Matter Antimatter Space Spectrometer.

trum. In fig. 2 the scheme of the MASS 89-91 instrument is shown.

HEAT

HEAT experiments, performed by an American collaboration, flew in two different configurations. The first was used in the 1994, 1995 flights from Fort Sumner and Lynn Lake, dedicated to electrons and positrons measurements. The instrument was composed of a Superconducting Magnet Spectrometer with a Drift Tube Hodoscope (DTH), of a Transition Radiation Detector (TRD) and an Electromagnetic Calorimeter (EC), placed respectively above and under the spectrometer, and of a Time-of-Flight (TOF) system. The second configuration, used in the 2000 flight from Fort Summer and dedicated to antiproton flux measurement, included the same magnetic spectrometer and two sets of Multiple Ionization (dE/dx) Detectors, placed respectively above and under the magnetic spectrometer, and the same Time-of-Flight (TOF) system.

BESS

The American and Japanese collaboration BESS conducted many flights, reported in Table 1, having the scientific objectives of the search for antiparticle and antimatter in the low energy region and for precise measurements of various primaries cosmic rays. The instrument was basically composed of a superconducting solenoid magnet and internal JET and drift chambers, with 1 Tesla uniform magnetic field and MDR of $\sim$ 200 GeV, for particle momentum and charge sign measurements. A Time-of-Flight hodoscope with three sets of scintillators placed, respectively, one on the top and two on the bottom of the solenoid vessel, determined particle velocity and charge absolute value; an aerogel Cherenkov counter was used for e/p rejection.

An important quality jump for antimatter and dark matter research with balloon-borne experiments has been done with the BESS Long Duration Flights performed from the base of William Field, McMurdo, Antartica, the POLAR I in 2004 (8.5 days long, and 1520 antiprotons detected in the energy range 0.1-4.2 GeV) and the Polar II in December 2007 (29.5 days with 24.5 of data taking). An example of the discrimination capability between particles and antiparticles of the BESS instrument is shown in fig. 3.

Although the first historical results were not confirmed, the way for a wide research for primary antimatter and dark matter signals in the cosmic rays was open. In 1998, on board the Space Shuttle, the AMS-01 collaboration performed the first antimatter experiment outside the atmosphere. In June 2006 the satellite experiment PAMELA was launched in orbit by a Soyuz-U rocket from the Bajkonur cosmodrome in Kazakhstan (Picozza et al. 2007).

3. Scientific results from Balloon Experiments

Two of the most compelling issues facing astrophysics and cosmology today have been addressed exploiting cosmic particles with the balloon borne experiments: the apparent absence of cosmological antimatter and

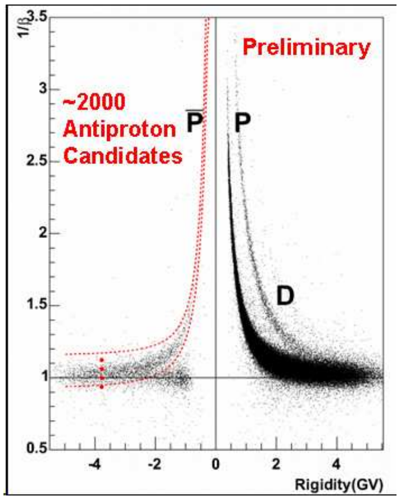

Fig. 3. Low Energy Antiproton Observed in BESS Polar I (2004).

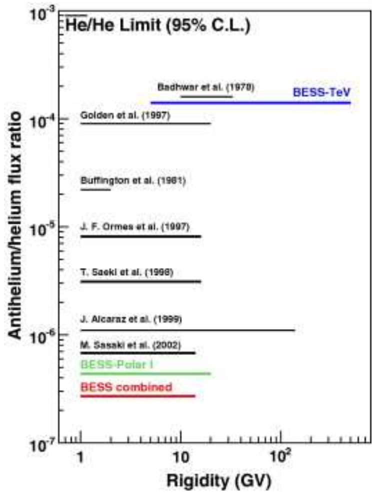

Fig. 4. Experimental limits for the $\overline{He}/He$ ratio.

the nature of the dark matter that pervades the Universe. What was the role of matter and antimatter in the early Universe? Is the present Universe baryon symmetric or baryon asymmetric? Is the matter only baryonic? Observation of the cosmic radiation holds out the possibility of directly observing a particle of antimatter that has escaped as a cosmic ray from a distant antigalaxy. The discovery of one nucleus of antimatter (Z≥2) in the cosmic rays would have profound implications for both particle physics and astrophysics. 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 abundant element to hydrogen. On the other side the detection of antinuclei with Z>2 in cosmic rays would provide, instead, direct evidence of the existence of antistellar nucleosyntesis. Moreover, several authors (Bambi & Dolgov 2007; Dolgov 2008) suggest that small bubbles with very high baryonic asymmetry could be been produced by the presence of stochastic or dynamical violation of CP also in a baryon dominate universe. The present experimental limits for antihelium/helium ratio, with a best value of 3×10^{-7}, obtained combining the BESS data, are shown in fig. 4.

As regards dark matter research it is now well-known that the energy budget of the Universe is shared among baryonic matter (4%), dark matter (23%) and dark energy (73%). The nature of the dark matter is still unknown. The favourite candidates for the non baryonic component are neutral weakly interacting massive particles (WIMP's) with a mass in the range between 10's of GeV to TeV. They would naturally appear as one of the thermal leftovers from the early Universe and their presence is predicted in several classes of extension of the Standard Model of particle physics. The most popular case is that of the lightest neutralino in R-parity conserving supersymmetric models. Considerable effort has been put into the search of dark matter WIMPs in the last 15 years with several complementary techniques applied. One way worth being explored is provided by indirect signatures. Neutralinos should pervade the Milky Way Halo and be concentrated in the galactic centre. As they mutually annihilate, they should produce high energy photons and antimatter cosmic rays. However these contributions are mixed with a huge background produced in the interactions of cosmic rays with the ISM, so that they will appear as a distortion of antiproton, positron and gamma energy spectra due to this secondary production.

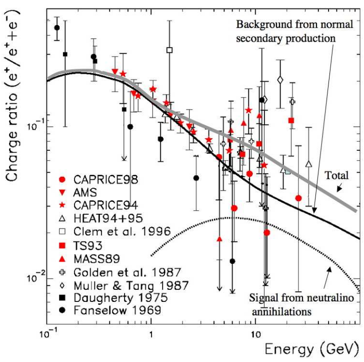

Fig. 5. Experimental data for $e^+/(e^+ + e^-)$ ratio, together with calculations for a purely secondary production, for a possible contribution from $\chi\chi$ annihilation and the sum of the two.

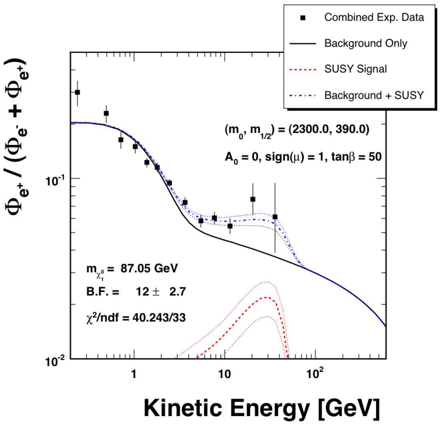

Fig. 6. Combination of the variuos experimental data for $e^+/(e^+ + e^-)$ ratio establishes a deviation from the expected background with a significance of more than four standard deviations (Chung et al. 2007).

In fig. 5 the experimental data for $e^+/(e^+ + e^-)$ are reported. An increasing or at least a flatness of the ratio appears clearly if compared with the standard production calculation. Moreover the combination of the various experimental data, shown in fig. 6, establishes a deviation from the expected background with a significance of more than four standard deviations (Chung et al. 2007). The observed change in the spectral index could be explained introducing a new source of positrons.

In fig. 7 the experimental results for the antiprotons flux are shown together with different theoretical calculations that account for a pure secondary component (Simon et al. 1998; Bergström et al. 1999) and a possible contribution from neutralino annihilation (Ullio et al. 1999). The large uncertainty in the background evaluation is due to a lack of knowledge of the experimental parameters used in solving the cosmic rays transport equation. Within the experimental and theoretical limits no particular strong contribution from exotic sources seems to be present. In fig. 8 the antiproton/proton experimental data together with background calculations from refs. (Molnar & Simon 2001; Bergström & Ullio 1999) are exposed.

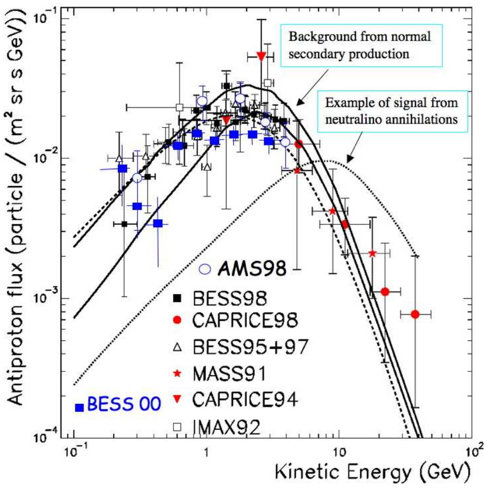

Fig. 7. Experimental data for the $\overline{p}$ flux together with calculations accounting for a pure secondary component (Simon et al. 1998; Bergström et al. 1999) and for a possible contribution from $\chi\chi$ annihilation (Ullio et al. 1999).

The antiprotons excess found in the early experiments had not been confirmed and the data seem to agree with a standard antiproton production. Moreover, in this graph the charge dependence of solar modulation clearly appears at low energy in the data collected by the same instrument, BESS, in different solar phases. Increasing solar activity strongly suppresses the low energy primary protons, while the secondary antiprotons are less affected because of their steeply decreasing spectrum in the low energy region. A much more rapid increase of the ratio was seen in BESS-2000, resulting from the dramatic suppression of the proton flux at solar maximum and the phase transition to the negative solar polarity. The asymmetric effect of the solar modulation and the uncertainty in the background calculation, both very important at low energy, must be taken in serious consideration if an exotic signal has to be disentangled from some standard production.

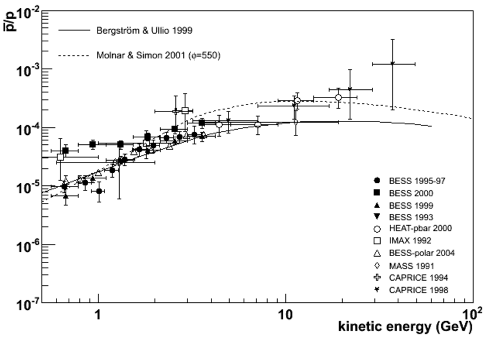

Fig. 8. Experimental data for $\overline{p}/p$ ratio together with background calculations (Molnar & Simon 2001; Bergström & Ullio 1999).

4. Summary

Many important aspects of antimatter presence in the Universe and of the nature of dark matter have had a first clarification by the ballon-borne experiments. An important limitation was due to the low statistics collected in the standard flights that reflects in a wide uncertainty in the interpretation of the results, especially in the search of dark matter signals. The last successful BESS Polar Duration Flights have opened a new era in cosmic rays research, with dedicated experiments and reasonable costs. PEBS (Positron Electron Balloon Spectrometer) designed to measure positrons and electrons in the energy range between 0.5 GeV to 200 GeV and DbarSUSY for search of Anti-deuterons in the energy range between 0.1 GeV to 2.5 GeV will be the next steps in the antimatter and dark matter research.

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