

Antimatter research in space

Piergiorgio Picozza and Aldo Morselli

University of Roma 'Tor Vergata' and INFN Roma 2, Roma, Italy

Received 18 October 2002

Published 9 April 2003

Online at stacks.iop.org/JPhysG/29/903

Abstract

Two of the most compelling issues facing astrophysics and cosmology today are to understand the nature of the dark matter that pervades the universe and to understand the apparent absence of cosmological antimatter. For both issues, sensitive measurements of cosmic-ray antiprotons and positrons, in a wide energy range, are crucial.

Many different mechanisms can contribute to antiprotons and positrons production, ranging from conventional reactions such as $p + p \rightarrow p + \bar{p} + \text{anything}$ up to exotic processes such as neutralino annihilation. The open problems are so fundamental (i.e., is the universe symmetric in matter and antimatter?) that experiments in this field will probably be of the greatest interest in the next years.

Here we will summarize the present situation, showing the different hypothesis and models and the experimental measurements needed to lead to a more established scenario.

1. Introduction

We must regard it rather an accident that the Earth and presumably the whole Solar System contains a preponderance of negative electrons and positive protons. It is quite possible that for some of the stars it is the other way about.

Paul Dirac in his speech accepting the Nobel Prize in Physics (1933)

The idea of exploiting cosmic antiprotons measurements to probe unconventional particle physics and astrophysics scenarios has a long history [1–10] and moved the cosmologists for several decades. Shortly after the discovery of the CP violation in the weak interactions in 1964, Sakharov formulated his famous hypotheses that were assumed to be a reasonable starting point to explain the apparent contradiction between the fundamental laws of nature and the observations. Several balloon-borne experiments were dedicated to the search for antiparticles and antinuclei, and in the 1970s the teams of Golden in USA [11] and of Bogomolov in Russia [12] identified the first antiprotons in cosmic rays (the positrons were discovered more than

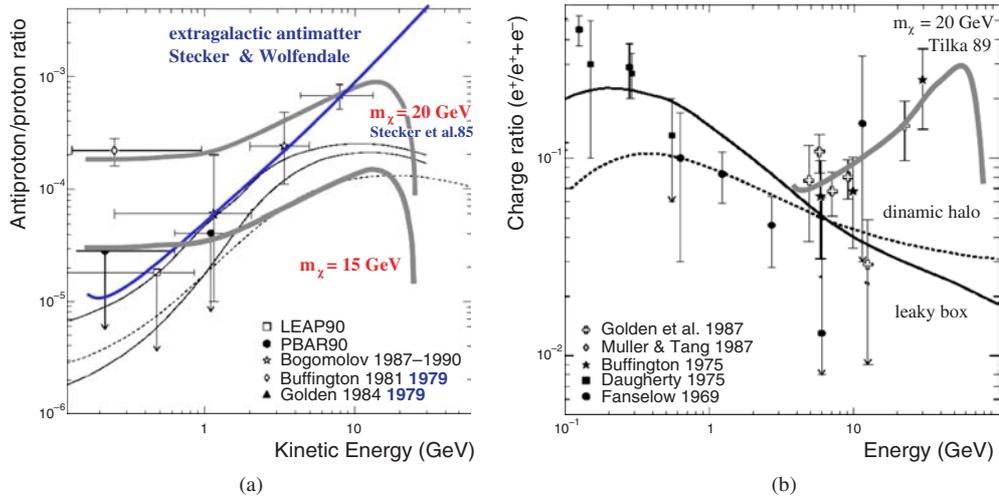


Figure 1. Antiproton/proton ratio experimental situation before 1990 (a). For the experimental data the references are: LEAP [13], PBAR [14], Bogomolov *et al* [12], Buffington *et al* [15], Golden *et al* [11]. Positron fraction experimental situation before 1990 (b) compared with the foreseen secondary production in the interstellar medium and an exotic model. For the experimental data the references are: Golden *et al* [16], Müller and Tang [17], Buffington *et al* [18], Daugherty *et al* [19], Fanselow *et al* [20].

40 years before by Anderson). Then, the antiproton spectrum was intensively studied for searching signals exceeding the background of the antiprotons produced in the interactions of CRs with the interstellar matter.

In figure 1(a) the data on the antiproton/proton ratio before 1990 are shown. At that time the standard production models (black lines) [21] could not account for all the antiprotons measured by the Golden *et al* and Buffington *et al* [15] experiments, and this triggered the formulation of many exotic models ranging from antiprotons coming from antigalaxies [22] to annihilation of supersymmetric dark matter (grey curve) [2].

In the same years the results of the positron ratio measurements were somewhat similar, with the experiments giving a higher flux of positron at energies greater than 10 GeV (see figure 1(b)), explained only with some exotic production, such as, again the annihilation of weakly interacting massive particles (WIMPs) giving a contribution as shown by the grey curve in figure 1 (from [23]).

2. The second generation experiments

In the last decade there has been an increase of experiments performed using novel techniques developed for accelerator physics. This has permitted us to improve the statistical and systematic significance of the experimental measurements. The WiZard collaboration did several balloon flights, MASS89 [24], MASS91 [31], TS93 [25], CAPRICE94 [26] and CAPRICE98 [27], exploring an energy interval from some hundreds MeV to 50 GeV of the antiproton and positron spectra.

The core parts of the instrument were a magnetic spectrometer composed of a superconducting magnet and a tracking system for charge sign and momentum measurements, an imaging calorimeter (streamer tube or silicon tungsten) and a β selector (Cerenkov, TRD or RICH).

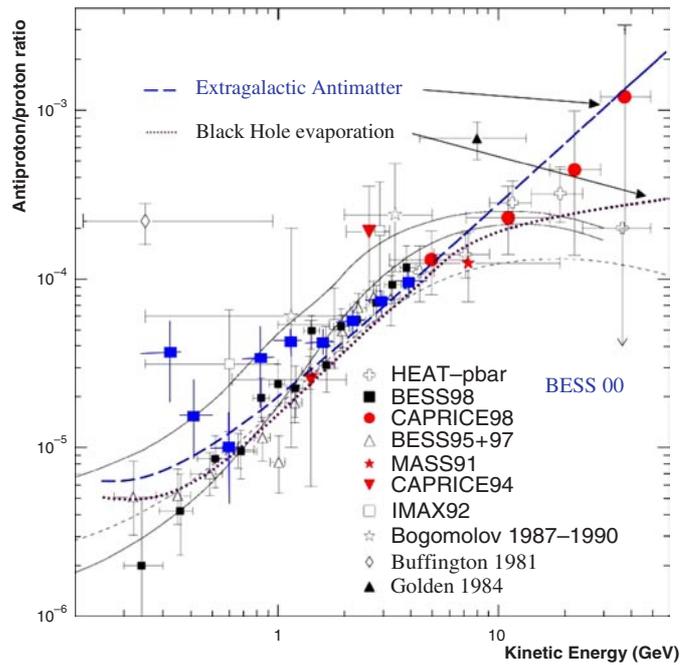


Figure 2. Antiproton/proton ratio: experimental data and theoretical predictions. For the experimental data the references are: BESS [28], Heat-pbar [29], CAPRICE98 [30], MASS91 [31], CAPRICE94 [32], IMAX92 [33], Bogomolov *et al* [12], Buffington *et al* [15], Golden *et al* [11].

In figure 2 the data for the antiproton/proton ratio collected up to now, together with the data of HEAT-pbar [34], HEAT [29] and IMAX92 [33] experiments, are reported.

The solid and dashed lines are, respectively, the theoretical interstellar and solar modulated ratios for a pure secondary origin of the antiprotons. The others are more exotic models.

Figure 3 shows the experimental results, including the AMS data [35], for the antiproton flux along with different theoretical calculations which account for a pure secondary component [42, 43] and together with the distortion on the antiproton flux (dashed line) due to a possible contribution from neutralino annihilation (dotted line, from [44]).

Figure 4 shows the experimental data for the $e^+/(e^+ + e^-)$ fraction together with the distortion (solid line) due to a possible contribution from neutralino annihilation (dotted line, from [45]).

The possibility of detecting this kind of distortion and then the possibility of discovering the nature of the dark matter is not so exotic as it might appear.

Over the last years our knowledge of the inventory of matter and energy in the universe has improved dramatically. Astrophysical measurements from several experiments are now converging and a standard cosmological model is emerging. For this model the density of the total matter is about $40\% \pm 10\%$ of the critical density of the universe, with a contribution of the baryonic dark matter less than 5% and a contribution from neutrinos that cannot be greater than 5%. The remaining matter should be composed of the yet-undiscovered weakly interacting massive particles (WIMPs), and a good candidate for WIMPs is the lightest supersymmetric particle (LSP) in R-parity conserving supersymmetric models.

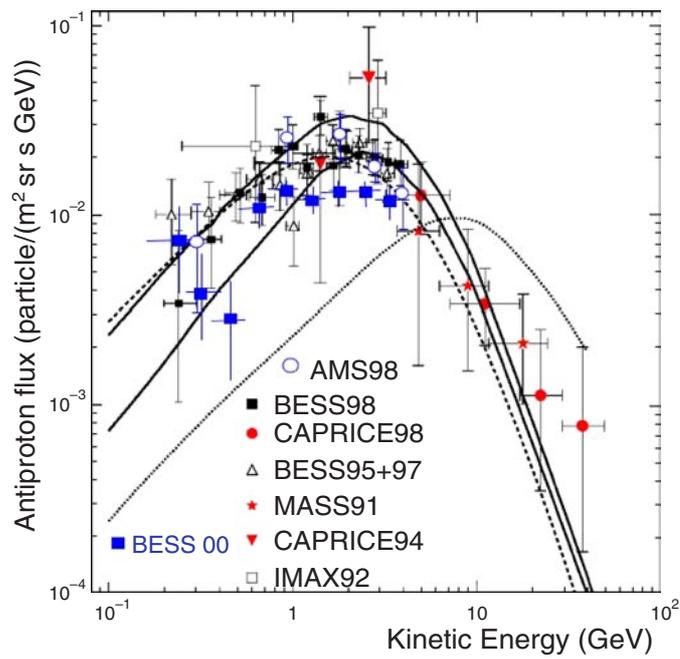


Figure 3. Antiproton absolute flux: experimental data and theoretical predictions.

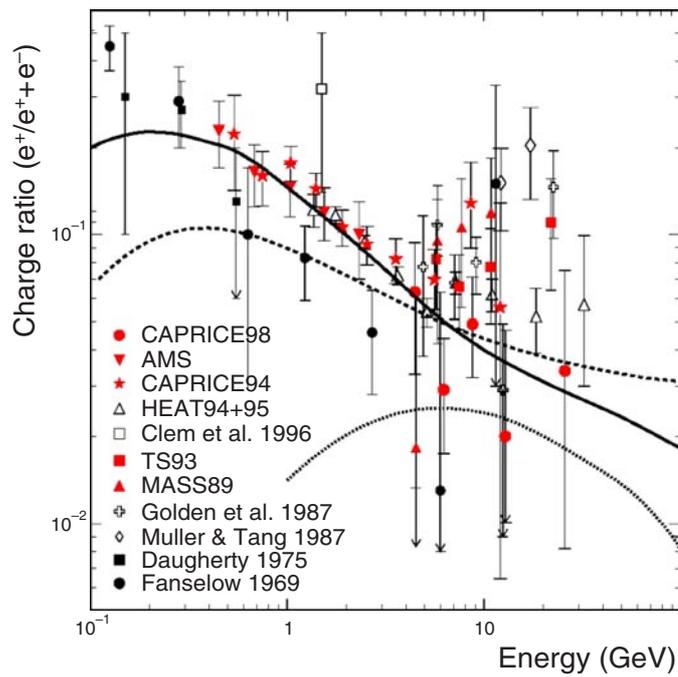


Figure 4. Positron fraction: experimental data and theoretical predictions. For the experimental results the references are: CAPRICE98 [36], AMS [37], CAPRICE94 [38], HEAT [29], Clem *et al* [39], TS93 [40], MASS89 [41], Golden *et al* [16], Müller and Tang [17], Fanselow *et al* [20].

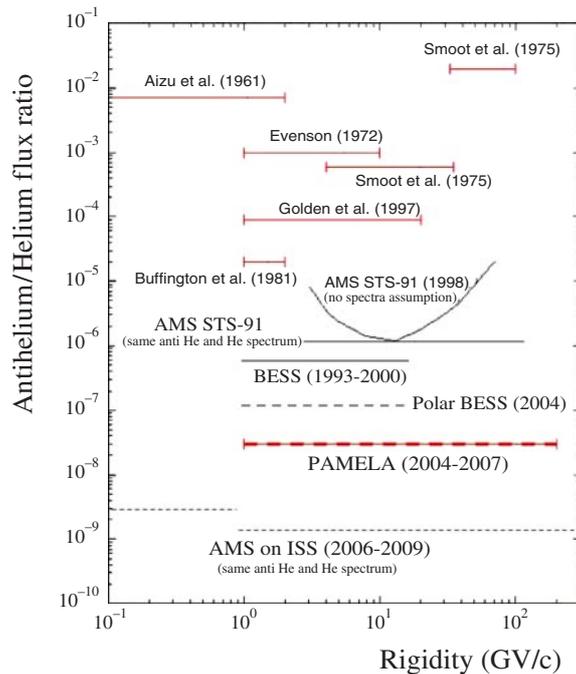


Figure 5. Present experimental limits for the antihelium/helium ratio and the sensitivities foreseen for the next experiments.

The best candidate as LSPs are the neutralinos. They are Majorana fermions and annihilate each other in the galactic halo producing leptons, quarks, gluons, gauge bosons and Higgs bosons. These decay and/or form jets that will give rise to antiprotons (and antineutrons which decay shortly to antiprotons), positrons and gammas. A description of the signature of the annihilation in gamma spectra can be found in [46]. From figures 3 and 4 it is clear that new experiments with better statistic are needed to discriminate among the models.

Another goal of these experiments is the search of antinuclei. Detection of heavy ($Z > 2$) antimatter of primary origin in cosmic rays would be a discovery of fundamental significance. That would provide direct evidence of the existence of antimatter in the universe. The current theory suggests that the remaining matter is the remnant of the almost complete annihilation of matter and antimatter at some early epoch, which stopped only when there was no more antimatter to annihilate. Starting from a matter/antimatter symmetric universe, the required conditions for a following asymmetric evolution are the CP violation, the baryon number non-conservation and a non-equilibrium environment. On the basis of gamma-ray observations, the coexistence of condensed matter and antimatter on scales smaller than those of clusters of galaxies has been virtually ruled out. However, no observations presently exclude the possibility that the domain size for establishing the sign of CP violation is as large as a cluster or super-cluster of galaxies. For example, there could be equality in the number of super-clusters and anti-super-clusters. Similarly, there is nothing that excludes the possibility of a small fraction of the cosmic rays observed at Earth, reaching our galaxy from nearby super-clusters. Up to now no antihelium or heavier antinucleus has been found. Figure 5 shows the present experimental limits and the sensitivities foreseen for the next experiments that will be discussed in the following paragraphs.

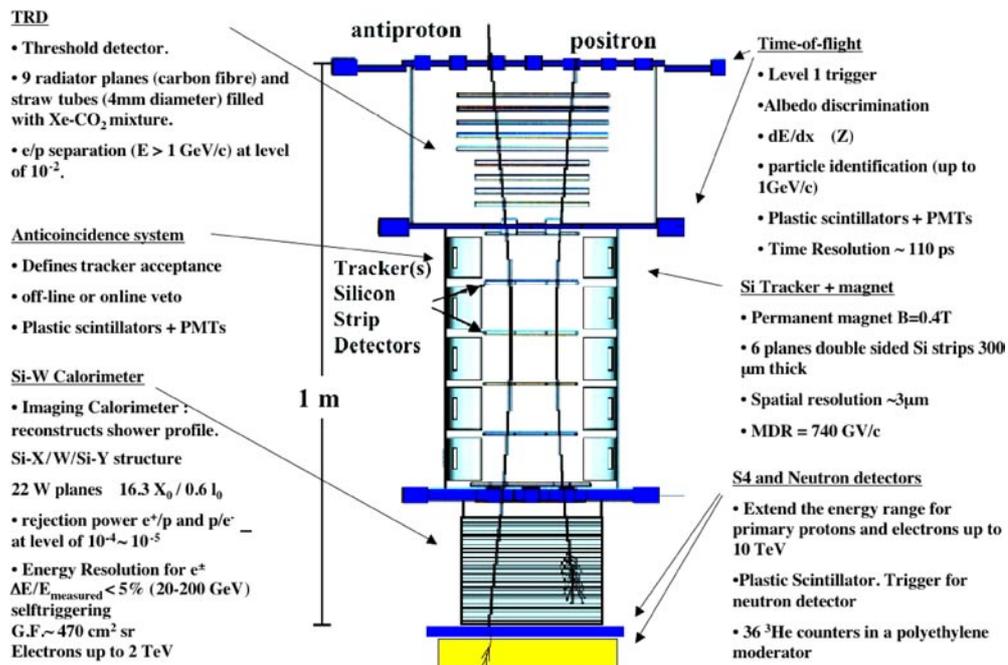


Figure 6. Schematic of the PAMELA baseline instrument.

3. The PAMELA mission

Three major experiments are being prepared for the future: the polar balloon BESS instrument, the satellite PAMELA experiment and AMS on the International Space Station.

The PAMELA telescope, shown in figure 6, is a satellite-borne apparatus built by the WiZard-PAMELA collaboration [47]. The list of people and the institution involved in the collaboration together with the online status of the project is available at <http://wizard.roma2.infn.it>.

3.1. PAMELA scientific objectives

The PAMELA scientific primary goal is the search for heavy nuclei and non-baryonic particles outside the standard model, for understanding the formation and evolution of our galaxy and the universe and for exploring the cycles of matter and energy in the universe. Additional objectives of PAMELA are the studies of galactic cosmic rays in the heliosphere, solar flares, distribution and acceleration of solar cosmic rays (SCRs) in the internal heliosphere, magnetosphere and magnetic field of the Earth, stationary and disturbed fluxes of high energy particles in the Earth's magnetosphere and anomalous components of cosmic rays.

The PAMELA observations will extend the results of balloon-borne experiments over an unexplored range of energies with unprecedented statistics and will complement the information gathered from the Great Space Observatories.

More precisely, during its three years of planned operation, PAMELA will measure with very high statistics:

- positron flux from 50 MeV to 270 GeV (present limits 0.7–30 GeV);
- antiproton flux from 80 MeV to 190 GeV (present limits 0.4–50 GeV);

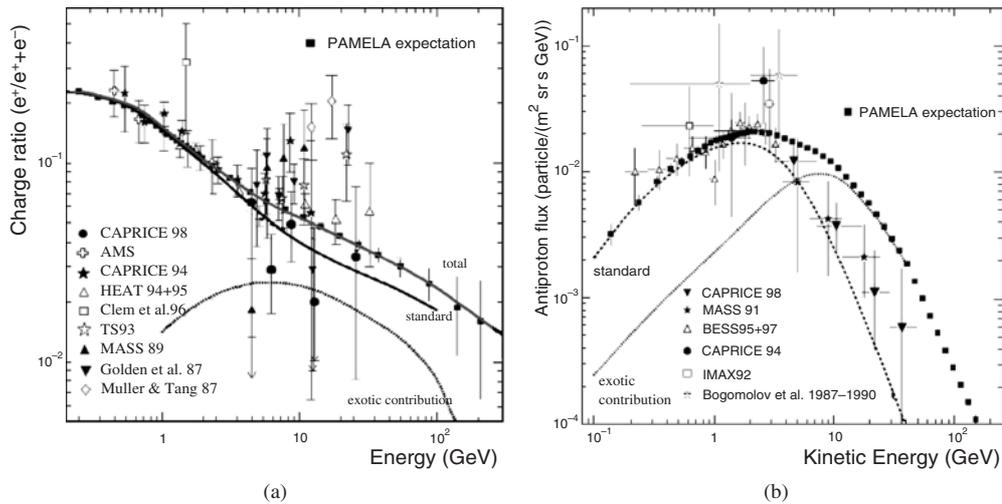


Figure 7. Distortion of the secondary positron fraction (a) and secondary antiproton flux (b) induced by a signal from a heavy neutralino. The PAMELA expectation in the case of exotic contributions are shown by black squares.

- limit on antinuclei $\sim 10^{-8}(\overline{\text{He}}/\text{He})$ (present limit about 10^{-6});
- electron flux from 50 MeV to 3 TeV;
- proton flux from 80 MeV to 700 GeV;
- light nuclei flux (up to oxygen) from 100 MeV/ n to 200 GeV/ n ;
- electron and proton components up to 10 TeV.

In addition it will assure a continuous monitoring of the cosmic rays solar modulation.

As an example, the expected data from the experiment PAMELA in the annihilation scenario for three years of operation are shown by black squares in figure 7 for both the positron and antiproton fluxes.

3.2. The PAMELA telescope

The PAMELA telescope, based on the experience gained in the WiZard balloon flights and in the WIZARD [48] on ASTROMAG and Mass-Sat [49] proposals, is composed of:

- A magnetic spectrometer to determine the sign of the electric charge and to measure the momentum of the particles. The magnetic system is composed of five permanent magnets of Nd-Fe-B, each 8 cm high, that provide a field inside the tracking volume of about 0.4 T. There are six planes of silicon micro-strip detectors for tracks reconstruction with a spatial resolution of $3 \mu\text{m}$ in the bending view giving a maximum detectable rigidity (MDR) of $740 \text{ GV}/c$.
- A transition radiation detector (TRD) for distinguishing at the level of 10^{-2} between electromagnetic and hadronic showers from 1 GeV to about 1 TeV; the TRD is based on small diameter straw tubes filled with Xe-CO₂ mixtures and arranged in double layer planes interleaved by carbon fibre radiator.
- A $16X_0$ silicon imaging calorimeter to discriminate at the level of 10^{-4} - 10^{-5} between electromagnetic and hadronic showers. It is composed of silicon strip sensors, interleaved with tungsten plates as converters. The energy resolution for positrons is of the order of $15\%/E^{1/2}$. In self-triggering mode the geometric factor of the calorimeter is about

470 cm² sr, allowing the measurement with useful statistics of the electron flux up to 2 TeV.

- Six scintillation counter (each 7 mm thick) hodoscopes for the event trigger and for TOF measurements with a time resolution of ~ 110 ps to provide albedo discrimination and particle identification up to 3 GeV/c.
- An additional plastic scintillator (S4 in figure 6) and a neutron detector composed of 36 ³He counters in a polyethylene moderator allow us, together with the imaging calorimeter, to extend the energy range for primary protons and electrons up to 10 TeV.
- A set of scintillation counters, covering part of the top edge, the lateral sides of the magnetic spectrometer and the bottom part of the calorimeter, completes the telescope, for a further labelling of contaminating events.

Others characteristics of the PAMELA instrument are:

1. an acceptance (geometrical factor) of 20.5 cm² sr;
2. a total volume of 120 × 40 × 45 cm³;
3. a total mass of 470 kg ;
4. a power consumption of 360 W.

The PAMELA instrument will be installed onboard the Russian RESURS-DK1 satellite, built by TsSKB-Progress. It will be launched in 2003 from Baikonur with a Soyuz TM rocket and placed on an elliptic orbit at an altitude of 300–600 km and an inclination of 70.4° for a mission at least three years long.

Averaging on the solar activity, in the first three years of the PAMELA flight (2003–2006) we expect to collect the following approximate numbers for particles, antiparticles and some nuclei:

Protons	3×10^8	Antiprotons	3×10^4
Electrons	3×10^6	Positrons	1×10^5
He nuclei	4×10^7	Be nuclei	4×10^4
C nuclei	4×10^5	Antinuclei limit	6×10^{-8} (90% CL)

References

- [1] Silk J and Srednicki M 1984 *Phys. Rev. Lett.* **53** 624
- [2] Stecker F W, Rudaz S and Walsh T F 1985 *Phys. Rev. Lett.* **35** 1
- [3] Stecker F W and Tylka A J 1989 *Astrophys. J.* **336** L51
- [4] Basini G, Morselli A and Ricci M 1989 *Riv. Nuovo Cimento* **12** 4
- [5] Silk J and Stebbins A 1993 *Astrophys. J.* **411** 439
- [6] Jungman G and Kamionkowski M 1995 *Phys. Rev. D* **51** 3121
- [7] Morselli A 1994 *The Dark Side of the Universe* (Singapore: World Scientific) p 267
- [8] Mitsui T *et al* 1996 *Phys. Lett. B* **389** 169
- [9] Morselli A 1997 *8th Marcel Grossmann Meeting (Jerusalem)* p 1465
- [10] Bottino A, Donato F, Fornengo N and Salati P 1998 *Phys. Rev. D* **58** 123503
- [11] Golden R *et al* 1979 *Phys. Rev. Lett.* **43** 1196
See also Golden R *et al* 1984 *Astrophys. J. Lett.* **24** 75
- [12] Bogomolov E *et al* 1987 *20th Int. Cosmic Ray Conf. (Moscow)* vol 2, p 72
Bogomolov E *et al* 1990 *21st Int. Cosmic Ray Conf. (Adelaide)* vol 3, p 288
- [13] Streitmatter R E *et al* 1989 *21st Int. Cosmic Ray Conf. (Adelaide)* vol 3, p 277
- [14] Ahlen S P *et al* 1988 *Phys. Rev. Lett.* **61** 145
- [15] Buffington A *et al* 1981 *Astrophys. J.* **248** 1179
- [16] Golden R L *et al* 1987 *Astrophys. J.* **287** 622

-
- [17] Müller D and Tang K K 1987 *Astrophys. J.* **312** 183
- [18] Buffington A *et al* 1975 *Astrophys. J.* **199** 669
- [19] Daugherty J K *et al* 1975 *Astrophys. J.* **198** 493
- [20] Fanselow J L *et al* 1969 *Astrophys. J.* **158** 771
- [21] Gaisser T K and Mauget B G 1973 *Phys. Lett.* **30** 1264
Gaisser T K and Schaefer R K 1992 *Astrophys. J.* **394** 174
Simon M and Heinbach U 1996 *Astrophys. J.* **456** 519
Mitsui T *et al* 1996 *Phys. Lett. B* **389** 169
- [22] Stecker F W and Wolfendale A W *19th Int. Cosmic Ray Conf. (La Jolla)* OG 6.1–8, p 354
- [23] Tilka A J 1989 *Phys. Rev. Lett.* **63** 840
- [24] Golden R *et al* 1991 *Nucl. Instrum. Methods A* **306** 366
- [25] Bocciaolini M *et al* 1993 *Nucl. Phys. B* **32** 77
- [26] Barbiellini G *et al* 1992 *Nucl. Instrum. Methods A* **371** 169
- [27] Bergström D *et al* 2001 *Nucl. Instrum. Methods A* **463** 161
- [28] Orito S *et al* 2000 *Phys. Rev. Lett.* **84** 1078
- [29] Barwick S W *et al* 1998 *Astrophys. J.* **498** 779
- [30] Bergström D *et al* 2000 *Astrophys. J.* **534** L177
Boezio M *et al* 2001 *Astrophys. J.* **561** 787
- [31] Basini G *et al* 1999 *26th Int. Cosmic-Ray Conf. (Salt Lake City)* vol 4, p 277
Hof M *et al* 1996 *Astrophys. J.* **467** L33
- [32] Boezio M *et al* 1997 *Astrophys. J.* **487** 415
- [33] Mitchell J *et al* 1996 *Phys. Rev. Lett.* **76** 3057
- [34] Beach A S *et al* 2001 *Preprint astro-ph/0111094*
- [35] Aguilar M *et al* *Phys. Rep.* **366** 331
- [36] Boezio M *et al* 1999 *26th Int. Cosmic-Ray Conf. (Salt Lake City)* OG.1.1.16
- [37] Alcaraz J *et al* 1999 *Phys. Lett. B* **461** 387
- [38] Boezio M *et al* 2000 *Astrophys. J.* **532** 653
- [39] Clem J M *et al* 1996 *Astrophys. J.* **464** 507
- [40] Golden R *et al* 1996 *Astrophys. J.* **457** L103
- [41] Golden R *et al* 1994 *Astrophys. J.* **436** 769
- [42] Simon M, Molnar A and Roesler S 1998 *Astrophys. J.* **499** 250
- [43] Bergström L, Edsjö J and Ullio P 1999 *Astrophys. J.* **526** 215
- [44] Ullio P 1999 *Preprint astro-ph/9904086*
Ullio P 2002 *Frascati Physics Series* vol 24th, p 475
- [45] Baltz E and Edsjö J 1999 *Phys. Rev. D* **59** 023511
- [46] Morselli A 2002 *Int. J. Mod. Phys. A* **17** 1829
- [47] Adriani O *et al* 1999 *24th Int. Cosmic Ray Conf. (Rome, 1995)* vol 3, p 591
Morselli A and Picozza P 1999 *The PAMELA apparatus for the search of antimatter in cosmic rays* *Topics in Cosmic-Ray Astrophysics* ed M DuVernois (Hauppauge, NY: Nova) p 37
- [48] Spillantini P *et al* 1989 *Nuovo Cimento B* **103** 625
- [49] Basini G *et al* 1990 *Nuovo Cimento B* **105** 779