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Observation of Antimatter in Our Galaxy

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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 like $p + p \rightarrow p + \overline{p} + anything$ up to exotic processes like neutralino annihilation. The open problems are so fundamental that experiments in this field are of the greatest interest.

Here we will summarize the present situation of the space experiments already flying or ready to fly or in preparation.

1. Introduction

The idea of exploiting cosmic antiprotons positrons and gammas measurements to probe unconventional particle physics and astrophysics scenarios has a long history ([1] and moved the cosmologists for several decades. After the discovery of the CP violation in the weak interactions, Sakharov in '67 formulated the three well known hypotheses that were assumed to be a reasonable starting point to explain the apparent contradiction between the fundamental laws of the nature and the observations.

The search for evidence of antimatter domains in the Universe can be undertaken with two main methods, an indirect one, looking for the spectrum of the Cosmic Diffuse Gamma, and a direct one by searching for heavy Antinuclei and by measuring $\overline{p}$ and e^+ energy spectra.

Concerning the gamma observation in the 100 MeV range, many physical processes in cosmic space can produce γ rays : in particular from interactions of cosmic protons and nuclei with the interstellar medium via π^0 decay. If we assume gamma produced also in proton-antiproton annihilation via π^0 decay, we can obtain an upper limit on the possible amount of annihilating antimatter and on the minimum separation among matter and antimatter domains. From the experimental data on the cosmic diffuse gamma spectrum [2] we obtain that the antimatter/matter fraction is $\leq 10^{-15}$ in the Galactic molecular clouds, $\leq 10^{-10}$ in the Galactic Halo, and $\leq 10^{-5}$ at the level of a cluster; so that we can conclude that if antimatter exists, it is separated from matter at least at the level of 50 Megaparsec.

A wide program of direct antimatter research (see Table 1) has been triggered by the results obtained in the 70's by the teams of R. Golden in USA [3] and of E. Bogomolov in Russia [4] (see figure 1) that identified the first antiprotons in cosmic rays. In fact the antiproton spectrum largely exceeded the expected antiprotons flux produced in the interactions of CR's with the interstellar matter [5]. Many exotic models ranging from antiprotons coming from antigalaxies [6] (blu line) to annihilation of supersymmetric dark matter (red curve) [7], was then promptly formulated to account for the excess.

Even the positron ratio measurements performed in the same years gave a too high flux of positron at energies greater than 10 GeV, explained by some exotic production, like again the annihilation of WIMPs.

1979	First Observation (Golden et al.)
1979	Russian PM (Bogomolov et al.)
1981	Excess reported (Buffington et al)
1985	ASTROMAG Study Started
1987	LEAP, PBAR (upper limits)
1991	MASS
1992	IMAX
1993	TS93, BESS
1994	CAPRICE94, HEAT93
1997	BESS
1998	CAPRICE98, AMS-01
1999	BESS
2000	HEAT-pbar, BESS
2004	BESS Polar I

Table 1. Antimatter in Cosmic Rays

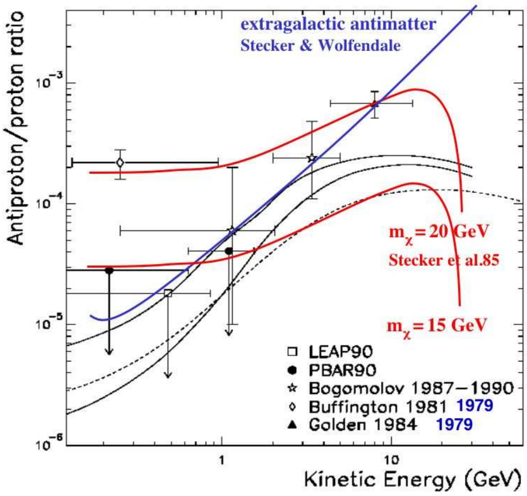

Figure 1. Antiproton/proton ratio: experimental situation before 1990.

In the last 20 years several balloon borne experiments have been performed using novel techniques developed for accelerator physics, mainly by WiZard (MASS89-91, TS93, CAPRICE94-98), HEAT and BESS Collaborations (see Table 1). In 1998 AMS01 flew onboard the Space Shuttle. The core part of all these instruments was a magnetic spectrometer associated with some detectors for hadronic and electromagnetic separation (for a review see [8]) .

In figure 2 there are the present experimental limits for the antihelium/helium ratio with a best value of the order of $3 \cdot 10^{-7}$ obtained combining all the BESS flights data.

In figure 3 are shown the experimental available results for the antiproton flux with different theoretical calculations which account for a pure secondary component, [9, 10, 11] and for a possible contribution from neutralino annihilation (dotted line, from [11]).

In figure 4 the experimental data for the $e^+/(e^+ + e^-)$ fraction are reported, with calculations of a pure secondary component (black solid line), a possible contribution from neutralino annihilation (dotted line, from[12]) and the total flux (grey solid line).

To disentangle these possible contributions of exotic components from the standard production, several space missions has been conceived for measurements at higher energies, with high statistics and during different solar modulation phases. These missions are shown in figure 5.

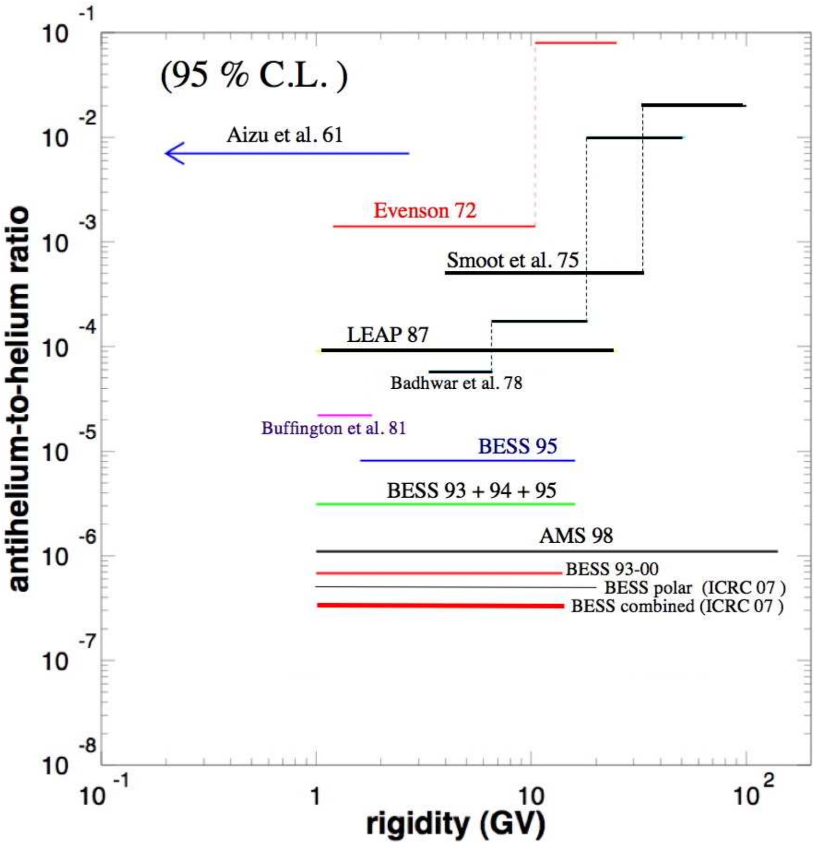

Figure 2. Present experimental limits for the antihelium/helium ratio

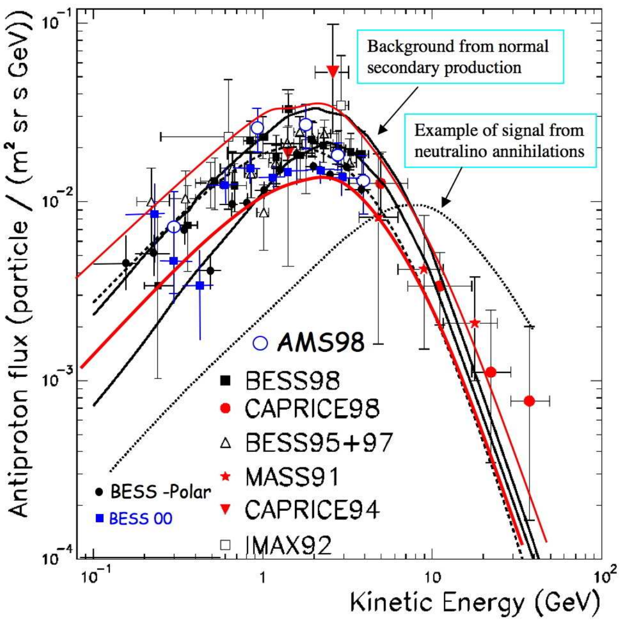

Figure 3. Antiproton flux: experimental situation and theoretical predictions

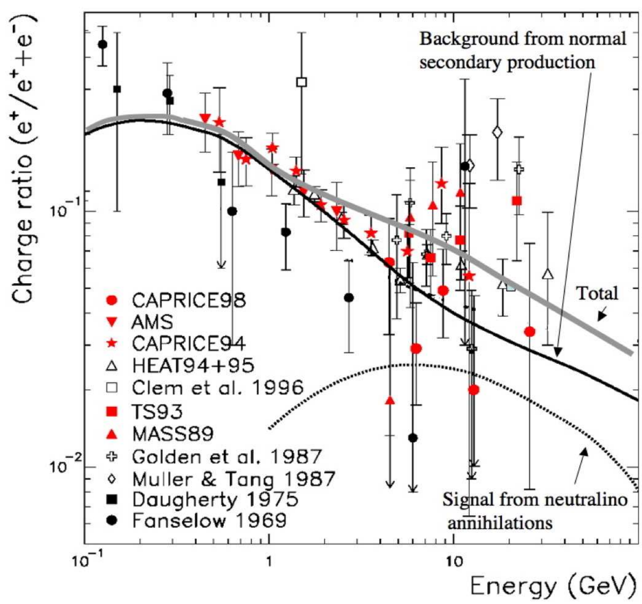

Figure 4. Positron fraction experimental situation and theoretical predictions

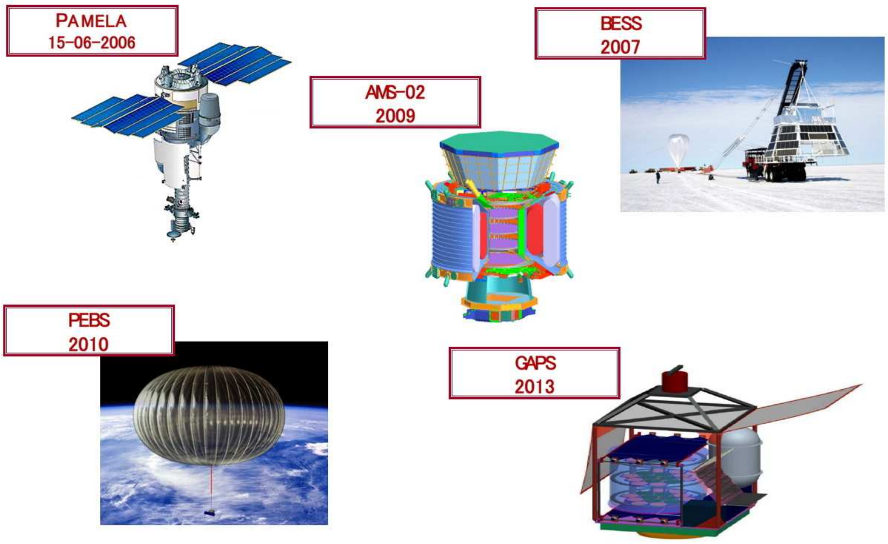

Figure 5. Antimatter and Dark Matter Space Missions

2. The PAMELA and AMS-02 Space Missions

The PAMELA and AMS-02 scientific primary goal is the search for heavy anti-nuclei and non baryonic particles outside the Standard Model, for the understanding of the formation and evolution of our Galaxy and the Universe and for the exploring of the cycles of matter and energy in the Universe. Additional objectives are the studies of galactic cosmic rays in the heliosphere, Solar flares, solar modulation, stationary and disturbed fluxes of high energy particles in the Earth's magnetosphere, anomalous components of cosmic rays. PAMELA (A Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) [13] was 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°.

The PAMELA collaboration is composed by six Italian Universities and INFN structures, three Russian research institutions and German and Swedish Universities. The instrument is constituted by a permanent magnet with a microstrip silicon tracker, a plastic scintillators time-of-flight system, a silicon-tungsten electromagnetic imaging calorimeter, an anticoincidence system, a shower tail catcher scintillator and a neutron detector. The combination of these devices allows antiparticles to be reliably identified from a large background of other charged particles. The weight is 470 Kg, the height 1.3 m and both the lateral dimensions 0.7 m. A scheme of the apparatus with flight events displayed is shown in figure 6.

PAMELA is in a continuous data-taking mode since July 2006. All systems are working as expected and scientific data analysis is now on-going.

More precisely, PAMELA is measuring with 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)
- Limit on antinuclei $\sim 10^{-8}(\overline{He}/He)$ (present limit about 10^{-6})
- Electron flux from 50 MeV to 2TeV
- Proton flux from 80 MeV to 700 GeV
- Light nuclei flux (up to oxygen) from 100 MeV/n to 200 GeV/n

In addition, it is assuring a continuous monitoring of the cosmic rays solar modulation.

A solar impulsive event proton spectrum is shown in figure 7 compared with the proton spectrum in a solar quite period.

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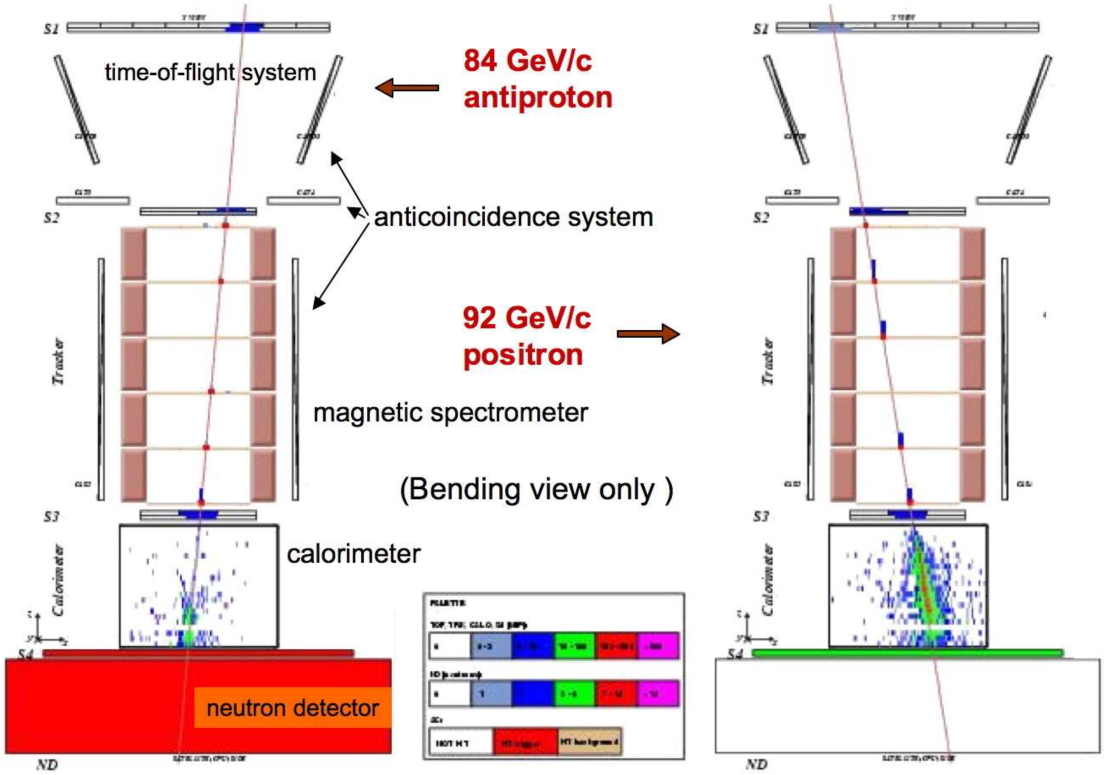

Figure 6. PAMELA Flight events. Bending views only are shown.

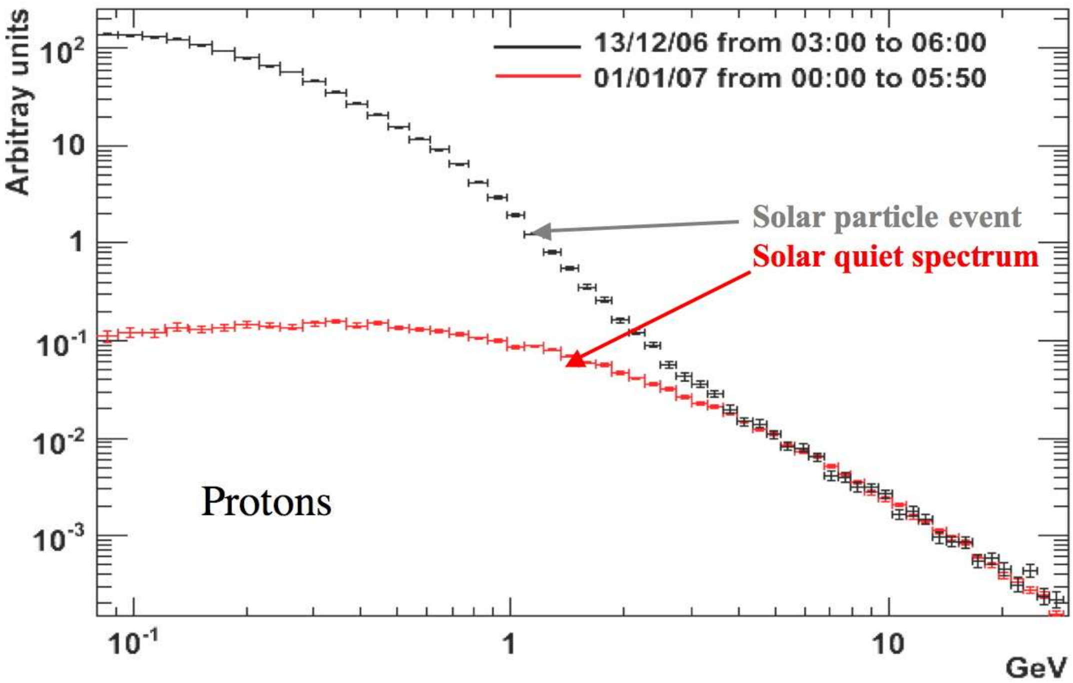

Figure 7. 13 December 2006 - Solar impulsive event.

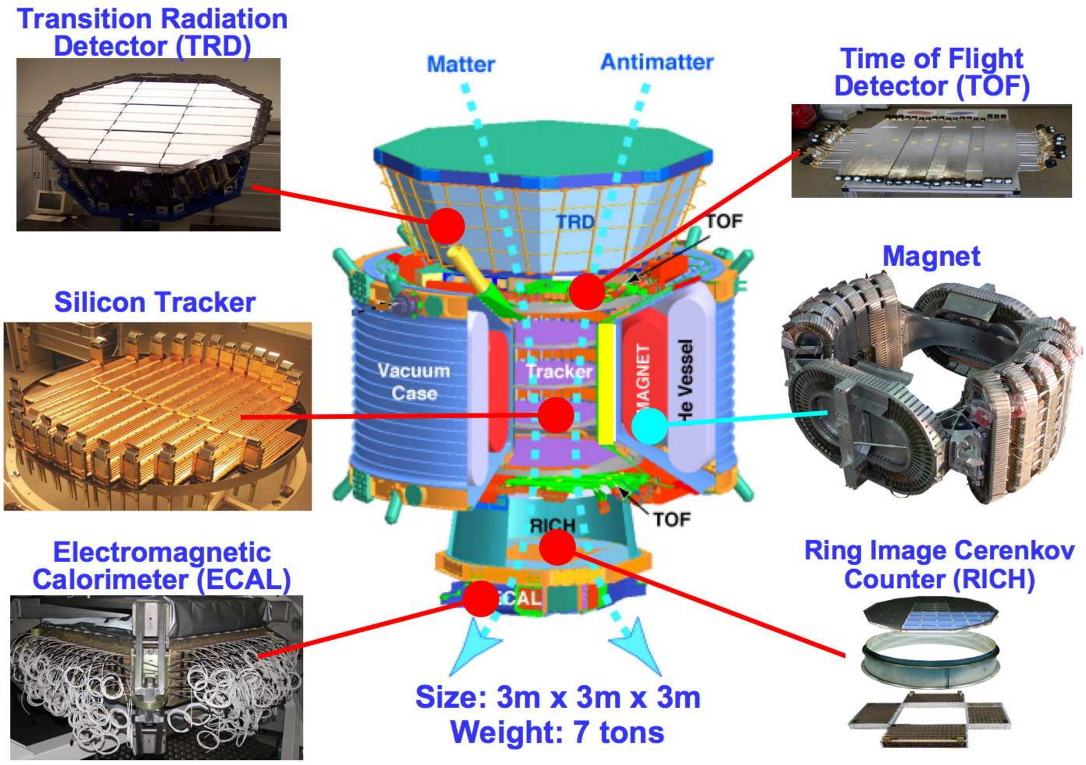

Figure 8. AMS-02 Detector

AMS-02 is a world wide collaboration. The detector in its assembling phase at CERN is shown in figure 8.

It is composed by a superconducting magnet with a microstrip silicon tracker, a strawtube TDR, a RICH, a scintillating fibers electromagnetic imaging calorimeter and a plastic scintillators time-of-flight system. The size is 3 m^3 and the weight is about 7 tons. It is foreseen to be launched in 2009. The large geometric factor, the high magnetic field and the number of different detectors will allow to enlarge the energy range explored by PAMELA, to improve the statistics and to do measurements of antideuterons and gammas.

3. Polar Balloon flights

New opportunities are given to the cosmic ray research at lower cost than space missions by long duration polar flights.

Most of the Antartic flights have flown around South Pole from $\sim$ 8 days up to 42 days.

In December 2007 BESS, an American-Japanese collaboration, will perform the second polar flight with a foreseen duration of $\sim$ 20 days. The Polar BESS long duration experiment features a instrument on the top of a payload with big omni directional solar panels in order to have enough power during the scheduled flight. It is composed by a superconducting solenoid with inside drift chambers as a tracker system. The time-of-flight is composed by plastic scintillators placed outside the magnet. An aereogel counter decreases the contamination of the electron particles.

It will have a good sensitivity to the low energy part of the CR spectrum and will perform a precise measurement of low energy antiprotons, antideuterons and antihelium.

An interesting possibility will be the contemporaneous measurements of BESS and PAMELA

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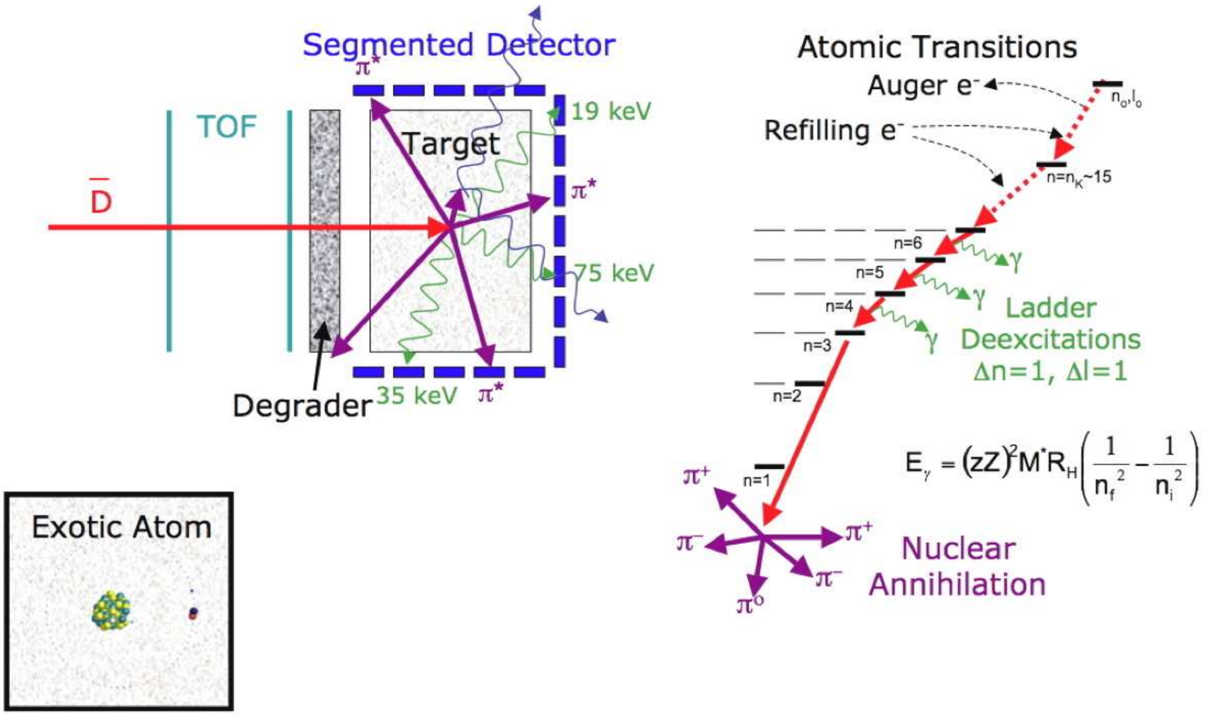

Figure 9. General Antiparticle Spectrometer (GAPS) general scheme.

instruments in the South Pole region.

The best measurements of antideuterons will be performed by the GAPS experiment [14] that will flight as a prototype in 2009 and in its final configuration in 2013. The method is shown in figure 9. The velocity of an antideuteron is measured by a TOF system and a degrader reduces the velocity by energy loss. In the active target the antideuteriun nearly at rest forms with a nucleus an exotic atom in an excited state. A precise measurement of the atomic transitions and of the nuclear annihilation products (mainly pions) allows for achieving comparable sensitivity to third-generation underground dark matter experiments.

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