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Search for Dark Matter signatures from cosmic-ray antinuclei with the GAPS experiment

Alessio Tiberio[a,*] **for the GAPS collaboration**

[a] *INFN, Sezione di Firenze,*
I-50019 Sesto Fiorentino, Florence, Italy

E-mail: alessio.tiberio@fi.infn.it

The General Antiparticle Spectrometer (GAPS) experiment is designed to perform low-energy cosmic-ray antinuclei measurements searching for indirect signatures of dark matter annihilation or decay. The unprecedented sensitivity at energies <0.25 GeV/n will allow GAPS to detect or set upper limits on the cosmic antideuterium or antihelium nuclei flux in an energy range with a very low astrophysical background. Several beyond-the-Standard Model scenarios predict antinuclei fluxes about two orders of magnitude above the astrophysical background. Furthermore, GAPS will collect the largest statistics of low-energy antiprotons to date, extending the existing measurements to unexplored low energies (< 100 MeV). The GAPS experiment will perform such measurements using long-duration balloon flights over Antarctica, beginning in 2022/23 austral summer. The experimental apparatus consists of ten tracker planes of Si(Li) detectors surrounded by a time-of-flight system made of plastic scintillators. A novel identification technique is used to detect the antinucleus, which employs the production and decay of a short-lived exotic atom. In this contribution, the status of the constructions of the different GAPS subdetectors will be reported, and the latest results of the simulations studies on the detector performance will be summarized.

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1. Introduction

The General AntiParticle Spectrometer (GAPS) [1, 2] is the first experiment designed for the observation of low-energy antinuclei, covering the energy region below 0.25 GeV/n. Several beyond-the-Standard Model theories predict a flux of antideuteron and antihelium nuclei from dark matter annihilation or decay several orders of magnitude above the astrophysical background in the energy region below few GeV/n [3, 4]: GAPS will therefore operate in an almost background-free energy region. The experiment will use a novel identification technique based on the formation of an exotic atom and the observation of its decay and annihilation products. GAPS will perform such measurements using long-duration balloon (LDB) flights over Antarctica. The first flight is expected to be performed in the 2022/23 austral summer and at least two other flights are planned. During its lifetime, GAPS will improve the sensitivity for antideuteron and antihelium nuclei by at least two orders of magnitude [5, 6]. Moreover, GAPS will collect the largest sample of antiprotons to date and it will extend the energy coverage in an unexplored low-energy region. In Section 2 the experimental apparatus is described, while the detection principle and the reconstruction algorithm are introduced in Section 3 Finally, in Section 4 the measurement capabilities of the experiment for antiprotons, antideuterons and antihelium are presented.

2. The GAPS experiment

The GAPS experimental apparatus consists of a time-of-flight (ToF) system surrounding several tracker planes. The ToF is arranged in an outer and an inner ToF systems made of plastic scintillator paddles. The outer ToF if made of and horizontal plane above the rest of the detector (named "umbrella") and of four lateral vertical walls (named "cortina"). The inner ToF is a cube that surround the tracker system on top, bottom and lateral sides. All scintillators are 6.35 mm thick and 16 cm wide, with a variable length between 1.1 and 1.8 m. Each paddle system provides the measurement of energy deposit, time and longitudinal position along its largest dimension [7]. The tracker systems is made of 1440 Si(Li) detectors arranged in 10 evenly spaced planes [8–11]. Each detector has a cylindrical shape of ~10 cm diameter and ~2.5 mm thickness and it is segmented into eight strips of equal area. The required operational temperature of ~-40° is achieved with an oscillating heat pipe system [12, 13]. The readout is performed with a dedicated ASIC [14]. In each plane 2×2 detectors are grouped into a module and 36 modules are arranged in a 6×6 array. The support structure of the planes is made of aluminum. A schematic view of the instrument is shown in Figure 1.

3. Detection principle

The detection principle is based on the obsevation of the annihilation products of the incoming antinucleus (hereafter called "primary"). The primary, after being slowed down by its ionization losses, can substitute an atomic electron (mostly in a silicon detector or in the aluminum frame) and form an exotic atom. The exotic atom then decays through a series of atomic transitions emitting characteristic X-rays [5], and the antinucleus finally annihilates with the target nucleus producing several secondary particles from a common vertex (mainly pions and protons). In order

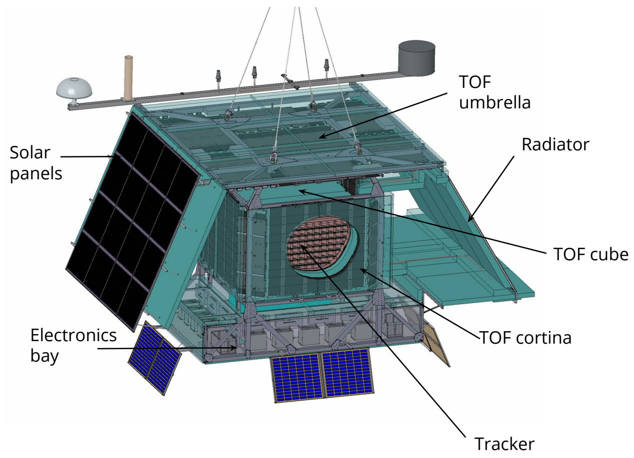

Figure 1: Schematic view of the GAPS experimental apparatus.

to discriminate antiproton nuclei from the cosmic ray background, a rejection power of at least 10^6 is required, taking into account the relative particle abundances (e.g., [15]). To measure a possible antideuteron component an additional 10^5 rejection factor is necessary to reject also antiproton background.

A precise reconstruction of the event topology is required to achieve these discrimination performances. A custom reconstruction algorithm has been developed for this experiment [16]. At first, the primary track is identified from the first two hits in the ToF. Then, a scan along the primary track is done in order to find the best tracks candidates for the annihilation products. Finally, the annihilation vertex is identified as the point that minimizes its distance from all the tracks. The method is iterated a second time after cleaning up the event from spurious hits and tracks. The algorithm exhibits a reconstruction efficiency of ~90% and the annihilation vertex is reconstructed with a precision of <10 cm (68% containment).

4. Sensitivity to antinuclei

Antideuteron nuclei have never been observed in cosmic rays and consequently any antideuteron detection would point to new physics. As can be appreciated in Figure 2, the predicted flux of a generic 70-GeV WIMP annihilating via the $b\bar{b}$ channel is at least two orders of magnitude above the astrophysical background in the energy region covered by GAPS [17]. The GAPS sensitivity in the 0.1−0.25 GeV/n region is expected to improve the previous upper limit established by BESS [18] by ~two orders of magnitude after three LDB flights The experiment is expected to be sensitive also to other dark matter models like right-handed Kaluza-Klein neutrino (from extra-dimensional grand unified theories), decaying LSP gravitino, next-to-minimal supersymmetric model (NMSSM), dark photon models, and heavy dark matter models with Sommerfeld enhancement.

The flux of antihelium nuclei predicted by several dark matter models is illustrated in Figure 3. After three LDB flights, GAPS has the possibility to probe dark matter models annihilating in the W^+W^- channel [6]. Eight antihelium candidates were reported by the AMS-02 collaboration, even

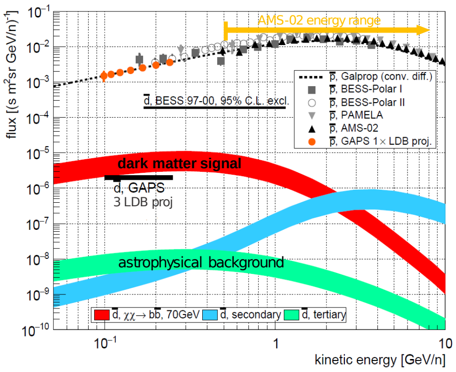

Figure 2: GAPS antideuteron sensitivity (black line) compared with the flux predicted by a generic 70 GeV WIMP (red band) and astrophysical background (cyan and green) models [5, 17]. BESS upper limit for the antideuteron flux is also shown. Orange points represent predicted antiproton flux measured by GAPS, while gray and black points represent antiproton measurements from previous experiments.

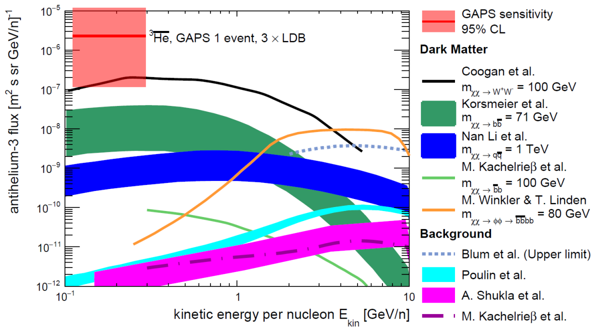

Figure 3: GAPS antihelium sensitivity (red line, with 95% C.L.) compared with the flux predicted by different dark matter and astrophysical background models [6].

if information on these events are not yet been published [19]. Since all reported AMS antihelium candidates have a momenta above 10 GeV/c, the GAPS experiment could test the existence of antihelium in the cosmic rays with an orthogonal measurement in a lower energy region and with a completely different detection technique.

In addition to antideuteron and antihelium searches, GAPS will provide a precise measurement of the antiproton spectrum in the 0.1–0.26 Gev/n region. Since dark matter annihilation/decay processes that produce antideuterons necessarily produce also antiprotons, a precise measurement of the antiproton spectrum provides constraints to antideuteron production in dark matter models. In particular, strong constraints will be set on dark matter candidates with a mass lower than ~30 GeV. The antiproton spectrum measurement will also provide detailed constraints on Galactic propagation models and will be a key ingredient to understand the attenuation and production of cosmic particles in the atmosphere. Moreover, the analysis of antiproton data collected during the first flight will give the possibility to validate the exotic atom identification technique and to provide a precise measurement of the background for heavier antinuclei studies.

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