The GAPS experiment: low-energy antinuclei measurements for dark matter searches

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Abstract. GAPS (General Anti-Particle Spectrometer) is a balloon-borne experiment designed to measure low-energy (<0.25 GeV/n) cosmic antinuclei (i.e., antiprotons, antideuterons, and antihelium nuclei) as a signature of dark matter annihilation or decay. According to viable beyond-the-Standard Model theories, the predicted dark matter signal in the low-energy antideuterons and antihelium nuclei channels is several orders of magnitude higher than the astrophysical background. The experiment will conduct a series of at least three long-duration balloon flights at high altitudes from Antarctica. The instrument is composed of a Si(Li) tracker surrounded by a Time-of-Flight system made of plastic scintillators. GAPS uses the novel exotic-atom detection technique in which an antinucleus is captured by the tracker material and forms an exotic atom. This excited exotic atom decays within the order of nanoseconds emitting X-rays at specific energies defined by the atomic transitions and annihilates emitting secondary particles (mainly pions and protons). The measured quantities (e.g., dE/dx, time of flight, annihilation vertex position, X-rays energies, etc.) allow for identifying antinuclei with high precision.

1 Introduction

The General AntiParticle Spectrometer (GAPS) [1, 2] is the first experiment devised to measure low-energy antinuclei, exploring the energy region below 0.25 GeV/n. According to viable beyond-the-Standard Model theories, the predicted dark matter (DM) signal in the low-energy antideuterons and antihelium nuclei channels is several orders of magnitude higher than the astrophysical background [3, 4]. In this scenario, GAPS will operate in an almost background-free energy region. The experiment will use a novel detection technique based on the formation and decay of exotic atoms. GAPS is planned to have at least three long-duration balloon (LDB) flights from McMurdo station in Antarctica. The first flight is expected to be performed in the austral summer of 2023-2024. GAPS will provide unprecedented sensitivity for antideuteron and antihelium nuclei [5, 6]. Moreover, GAPS will perform high statistic measurements of antiprotons and extend the energy coverage in an unexplored low-energy region [7].

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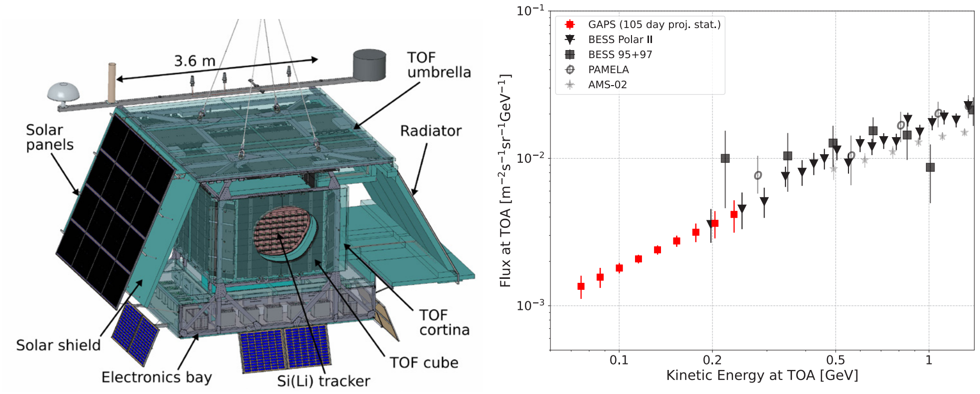

Figure 1. Left panel: A schematic view of the GAPS detector. **Right panel**: The GAPS sensitivity for cosmic antiproton spectrum (red) at the top of the atmosphere is shown with the statistics expected from three 35-day flights [7]. Data from BESS (1995 and '97 [12]), BESS Polar II [13], PAMELA (2006−09 [14]), and AMS-02 (2011−18 [15, 16]) are also shown.

2 The GAPS detector

Fig. 1 (left panel) shows a schematic view of the GAPS apparatus consisting of a Time-of-Flight (ToF) and tracking systems.

The ToF system consists of ∼160 plastic scintillator paddles [8] and is arranged in an outer Tof system and an inner Tof system. The outer ToF consists of an umbrella of scintillator oriented horizontally and a cortina of four walls of scintillator oriented vertically. The inner ToF is a cube of scintillator paddles, consisting of four sides, a top and a bottom. The ToF system measures the time information necessary to reconstruct the velocity of particles and the ionization energy losses dE/dx of particles. The ToF also provides the overall trigger for GAPS.

The core of the apparatus is a tracking system made of ten planes of 12×12 cylindrical Si(Li) detectors each [6, 9]. For the first flight, ∼1000 Si(Li) detectors will be equipped. On each supporting aluminum plane, the Si(Li) cylinders are arranged in a 6×6 array of modules, each with four Si(Li) detectors read out by a dedicated ASIC [10]. The Si(Li) detectors have a diameter of ∼10 cm, are ∼2.5 mm thick and are segmented into eight strips of equal area. Finally, the tracking system is kept at its operational temperature of ∼-40° C by an oscillating heat pipe (OHP) thermal system [11].

3 Detection technique

GAPS uses a novel technique for antinuclei detection, based on the formation and decay of exotic atoms. The incoming primary antinucleus slows down due to ionization energy losses in the materials of the apparatus and, after losing all kinetic energy, can form an exotic atom by replacing a shell electron in a silicon or aluminum atom. During the de-excitation process, the exotic atom emits characteristic X-rays with energies determined by atomic transitions [5]. In the end, the primary particle annihilates with the target nucleus producing secondary particles, mainly pions and protons from a common vertex. The measurements of the time-of-flight, ionization losses dE/dx, and X-ray energies together with the reconstructed topology of the "annihilation star", allow to clearly identify antinuclei.

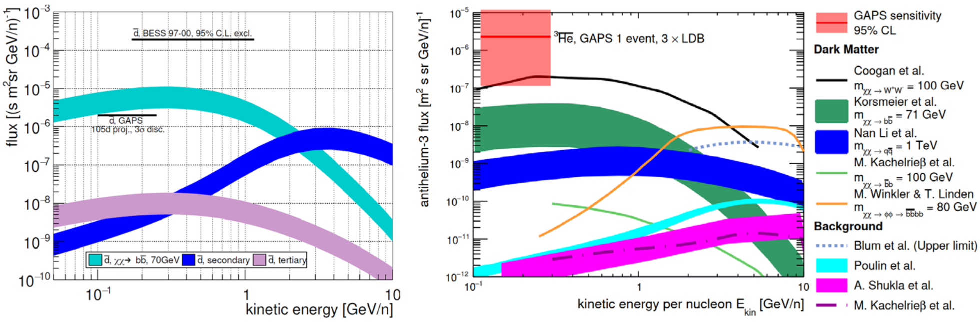

Figure 2. Left panel: the predicted antideuteron flux from a generic 70-GeV WIMP annihilating via $b\bar{b}$-pairs (cyan), as well as the predicted secondary (blue) and tertiary (pink) astrophysical antideuteron flux. The anticipated sensitivity of GAPS [5, 19] for a 3 σ discovery and the BESS 97–00 95% C.L. exclusion limits are shown [20]. **Right panel**: GAPS antihelium sensitivity (red line, with 95% C.L.) compared with the flux predicted by different dark matter and astrophysical background models [6].

In order to reconstruct the antinucleus annihilation topology, a custom algorithm was developed. First, the primary track is identified, followed by the secondary tracks associated with the primary track. Finally, the annihilation vertex is defined as the point which minimizes the distance between primary and secondary reconstructed tracks [17].

4 Antinuclei sensitivity

The sensitivity curves for antinuclei were determined using the GAPS simulation software, which reproduces the instrument geometry and materials using the Geant4 toolkit [18]. Moreover, a digitization process was applied to the simulated data to mimic a realistic instrument response for time, energy, and position measurements.

Fig. 1 (right panel) shows the expected antiproton measurement at the top of the atmosphere (TOA) for three ∼35 day antarctic flights at ∼37 km float altitude [7]. The GAPS precision measurement of antiprotons in this unexplored low-energy range will have about two orders of magnitude more low-energy antiprotons than BESS [12, 13] and PAMELA [14] combined, i.e., ∼500 antiprotons expected for each flight. These measurements will provide strong constraints on DM candidates with masses <30 GeV and primordial black hole evaporation on Galactic length scales [19].

Antideuteron nuclei have never been observed in cosmic rays, and any detection would be sufficient to claim the discovery of new physics. Fig. 2 left pannel shows the GAPS sensitivity to low-energy cosmic antideuteron after three LDB flights, compared with the antideuteron fluxes expected from a generic 70-GeV WIMP annihilating into antideuterons via $b\bar{b}$-pairs (cyan) [5, 19]. As described in Sec. 1, the astrophysical background (blue and pink) is at least two orders of magnitude below the expected DM signal [21].

The flux of antihelium nuclei predicted by several dark matter models is illustrated in Figure 2, right panel. Three GAPS LDB flights will provide enough sensitivity to low-energy antihelium-3 nuclei, with the potential to probe dark matter models annihilating into W^+W^- [6].

Due to its novel detection technique and sensitivity to the lower-energy range, where the predicted contribution from most of the new-physics models is highest, GAPS will provide complementary measurements to the experiments operating so far.

Acknowledgements

This work is supported in the U.S. by the NASA APRA program (Grant Nos. NNX17AB44G, NNX17AB46G, and NNX17AB47G), in Japan by the JAXA/ISAS Small Science Program FY2017, and in Italy by Istituto Nazionale di Fisica Nucleare (INFN) and the Italian Space Agency (ASI) through the ASI INFN agreement No. 2018-22-HH.0: "Partecipazione italiana al GAPS - General AntiParticle Spectrometer." H. Fuke is supported by JSPS KAKENHI grants (JP17H01136, JP19H05198, and JP22H00147) and Mitsubishi Foundation Research Grant 2019-10038. The contributions of C. Gerrity are supported by NASA under award No. 80NSSC19K1425 of the Future Investigators in NASA Earth and Space Science and Technology (FINESST) program. R. A. Ong receives support from the UCLA Division of Physical Sciences. K. Perez and M. Xiao are supported by Heising-Simons award 2018-0766. F. Rogers is supported through the National Science Foundation Graduate Research Fellowship Program under Grant No. 1122374. Y. Shimizu receives support from JSPS KAKENHI grant JP20K04002 and Sumitomo Foundation Grant No. 180322. M. Yamatani receives support from JSPS KAKENHI grant JP22K14065. K. Yee is supported through the National Science Foundation Graduate Research Fellowship under grant 2141064.

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