PROCEEDINGS OF SCIENCE

# The GAPS experiment - a search for light cosmic ray antinuclei

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The General Anti Particle Spectrometer (GAPS) is a balloon-borne cosmic-ray experiment which is currently in its last phase of construction, undergoing system testing, and scheduled for a long-duration balloon flight from McMurdo Station in the Antarctic in December 2024. Its primary scientific goal is the search for light antinuclei in cosmic rays at kinetic energies below 0.25 GeV/$n$. This energy region is especially of interest for beyond-the-standard model dark matter searches and is still mostly uncharted. Searches for light antimatter nuclei with energies below 0.25 GeV/$n$ are a novel approach to the search for dark matter because wide range of dark matter models proposes annihilation or decay into matter-antimatter pairs. GAPS will yield unprecedented sensitivity to low-energy antideuterons and will measure the low-energy antiproton spectrum with high statistics and precision. To reach the required sensitivity, the GAPS detector incorporates a new approach for antimatter detection, utilizing a tracker with custom, lithium-drifted silicon detectors, designed to measure the X-ray cascade expected from antimatter capture and charged particles from the subsequent annihilation. It also utilizes a fast time-of-flight system, allowing for a high-precision beta measurement. This proceeding highlights GAPS scientific goals.

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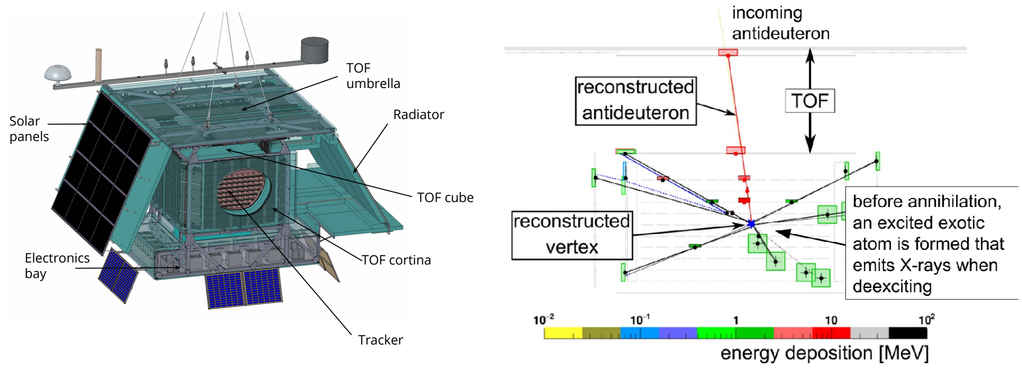

**Fig. 1:** *Left:* A schematic overview of the GAPS instrument: Indicated are the three components of the time of flight (TOF) system as well as the Si(Li) tracker. *Right:* A $\bar{d}$ annihilating in the tracker forming an exotic atom in the process and resulting in a final state with several pions.

## 1 Introduction

In modern physics, the question of the nature of dark matter (DM) is of major importance. Our current understanding of the universe relies on the inclusion of this yet-to-be-identified matter component, currently presenting itself to the observer only through gravitation [1].

Proposed methods for dark matter detection include observing its decay or annihilation products, which might include antinuclei. While antiprotons have been measured in cosmic-ray data [2], conclusive results about their origin are still under debate due to uncertainties in the astrophysical background predictions [3]. Especially secondary $\bar{p}$ fluxes from $pp \Rightarrow p+p+\bar{p}p+\ldots$ at sufficiently high energies are not well understood yet and pose a challenge for uncovering the observed $\bar{p}$ origin. This makes heavier antinuclei such as antideuterons very interesting, since the predicted fluxes for heavier astrophysical antinuclei at low energies ($0.1 - 0.3\,\mathrm{GeV}/n$) are about 3 orders of magnitude below the predicted fluxes for a variety of dark matter models [3].

The General Antiparticle Spectrometer (GAPS) has been proposed as an indirect dark matter detection experiment optimized to detect these low-energy ($0.1 - 0.3\,\mathrm{GeV}/n$) cosmic antinuclei using a series of Antarctic long-duration balloon (LDB) flights [4]. The GAPS detection principle does not rely on a magnet and is further described in Section 2. It utilizes the so-called "exotic atom technique" : Similar to a muonic atom, an exotic atom is formed when an antinucleus replaces electrons in the shell of a target atom. This configuration is unstable, and when decaying, the antinucleus will emit a series of characteristic X-rays in the process, which can be used to identify the antinucleus. Ultimately, the antinucleus will annihilate with the nuclei, emitting secondaries.

The GAPS scientific payload has been assembled, completed a series of thermal-vacuum tests, and is preparing for its launch in December 2024. Its expected science capabilities for $\bar{p}$, $\bar{d}$ and $\bar{\alpha}$ are outlined in Section 3.

## 2 The GAPS experiment

### 2.1 Instrument overview

The GAPS science instrument is a payload of approximately 2300 kg which will be attached to a balloon suitable for a long-duration balloon flight (LDB) from McMurdo, Antarctica. The first launch is planned for December 2024.

GAPS has two major detector components, a time-of-flight system (TOF) as well as a Si(Li) tracker. To account for the limited power, weight limitations, and reduced bandwidth for data transmission for balloon experiments, GAPS features specifically designed detectors and readout. This includes the utilization of SiPMs for the TOF system, the usage of lightweight styrofoam to hold the individual tracker detectors, a novel passive heat pipe system, and extensive onboard data processing utilizing low-power CPUs. A schematic of the payload is shown in Figure 1.

The TOF system is made of 160 individual scintillator paddles. Each scintillator paddle is read out by 6 SiPMs on each end. The individual paddles are arranged in three main components: A cube, wrapped tightly around the GAPS tracker, a cortina which is a layer around the cube and an umbrella which is a large panel of scintillator paddles on top of the instrument above 1m above the cube.

The umbrella provides a large angular acceptance for the trigger. The two panels are at a distance of about 1m, which does allow for a precise measurement of the incoming primary velocity. Dedicated electronics allow for a tunable trigger based on threshold crossing of the recorded signal in the individual paddles. A so-called master trigger which receives the signal of all paddles over threshold can use pre-programmed paddle combinations, the value of the crossed threshold as well as a measured velocity estimate to provide the global trigger decision. The trigger will reduce the individual, per paddle rate of about 2kHz to a global trigger rate of about 500Hz. Besides providing the trigger, the TOF system records the SiPM waveforms with dedicated electronics utilizing a DRS4 chip. While providing important information about the incoming primary, the TOF is also recording the signals of the secondary particles leaving the tracker after an annihilation. After the waveforms are recorded, they are processed onboard, and a low-power CPU will analyze the event, providing a more precise $\beta$ estimate as well as categorizing it by event quality, allowing it to impose filter criteria. These filter criteria can then be used to decide which events will be transmitted to the ground.

The GAPS tracker has 10 individual tracker layers, 7 of them instrumented with 252 active modules, where a module is an integration unit of 4 individual detectors. The Si(Li) detectors are of custom design and feature a large diameter (4") and are segmented into 8 distinct strips [7]. The detectors are read out by a custom-designed ASIC [6], featuring a wide dynamic range allowing to measure X-rays from $20 - 100$ keV as well as the energy depositions of heavier cosmic-ray (anti)nuclei up to 100 MeV. The Si(Li) detectors can be operated at high temperatures for such detectors of $-40\ ^{\circ}C$. This allows for passive cooling, which is provided by a newly designed oscillating heatpipe system [8].

### 2.2 Detection technique

The instrument is optimized to detect slow-moving ($\beta \approx 0.2 - 0.5$) antinuclei with single or double charge. Signal identification relies on a precise measurement of the particle's velocity, a calorimetric energy measurement, tracking of the annihilation products as well as the measurement of de-excitation X-rays from exotic atoms.

The measurement principle is illustrated in Figure 1. A primary particle, in this case, an antideuteron, passes through the umbrella part of the TOF as well as its upper cube panel, providing a $\beta$ measurement as well as a measurement of the deposited energy along its track. The antideuteron then gets captured by a silicon nucleus in one of the tracker detectors, forming an exotic atom in the process. In these atoms, the incoming antinucleus replaces an electron in the shell before emitting de-excitation X-rays with energies of several 10keV. This exotic atom is decaying almost instantaneously when the antideuteron annihilates with nucleons of the Silicon, resulting in emerging pions and kaons. The decay products are registered by the tracker and TOF and the observed star pattern can be reconstructed to help determine the annihilation vertex, together with the reconstructed incoming primary track. Energy deposition patterns along the tracks together with multiplicity and velocities of secondaries as well as the de-excitation X-rays are used in the identification of the particle species.

## 3 GAPS scientific goals

A confirmed detection of a single cosmic antideuteron would be the first of its kind. Besides being a groundbreaking discovery on its own, antideuterons can help to resolve the antihelium puzzle [3]. Antinuclei have to be the product of their constituents and assuming that the probability for the constituents to coalesce into an antinucleus drops rapidly with the number of constituents, antideuteron formation should be much more likely than antihelium formation. In light of the tentative antihelium candidates reported by the AMS-02 collaboration, this means that an antideuteron measurement by GAPS might help understand the origin of the AMS-02 antihelium candidates. GAPS is not only capable to search in an energy range complimentary to AMS-02, but it also uses a different detection technique with different systematic errors.

The GAPS capabilities have been investigated with large-scale MC simulation productions of various (anti)particle species. The simulation includes modeling of the trigger algorithm, a realistic geometry, including crucial passive detector components close to the Si(Li) detectors, as well as an approximation for the digitization and data processing electronics.

### 3.1 Antiproton spectrum

The antiproton spectrum is projected to be measured with unprecedented statistics in the low-energy range. GAPS is expected to measure about 500 antiprotons per 30-day flight in an energy range of $\approx 0.07 - 0.21$ GeV/$n$ at the top of the atmosphere. Not relying on the more traditional approach of a magnetic spectrometer, this measurement will provide a sizeable sample with orthogonal systematics in an energy range where no previous measurements have been conducted [9].

The analysis considers downgoing primaries with $0.25 < \beta < 0.65$. For particle identification, a series of variables are used which are mainly focussing on the energy deposition pattern along the

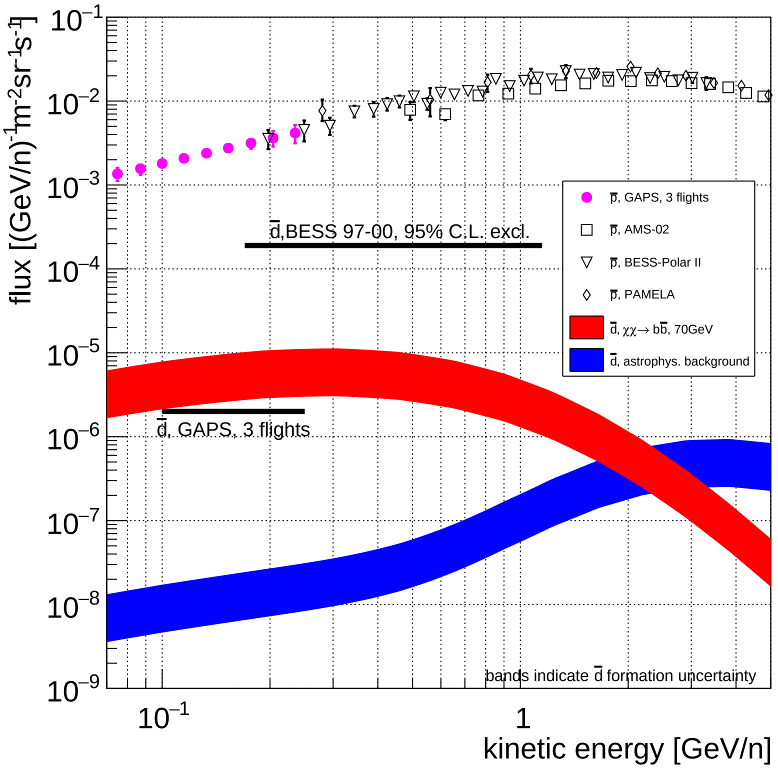

**Fig. 2:** The projected cosmic antiproton spectrum at the top of the atmosphere together with the antideuteron sensitivity. Flux prediction for $\bar{d}$ from a generic WIMP annihilation model as well as astrophysical background predictions are shown as well. Data from BESS, AMS-02 and PAMELA taken from [2, 11, 14, 15, 17]

track, the quality of the event reconstruction as well as the properties of the secondaries from the annihilation. The projected spectrum is shown in Figure 2. It extends previous measurements well into the energy range below 200 MeV/$n$ with very small statistical errors.

### 3.2 Antideuteron sensitivity

In a similar way as for the antiproton analysis, the sensitivity for antideuterons has been derived. The sensitivity is constructed in such a way, that a single, confirmed antideuteron event will provide a 3-$\sigma$ discovery. The projected antideuteron sensitivity for GAPS is shown in Figure 2. The expected astrophysical backgrounds in this energy range are below the expected signal from many dark matter models by about 3-4 orders of magnitude. The shown dark matter signal is derived from a 70 GeV WIMP annihilation model. The projected GAPS sensitivty improves over the BESS limit [11] by over two orders of magnitude. The model-independent approach to search for antideuterons allows constraining a wide variety of DM models which emerged in recent years with a large variety of antideuteron production mechanisms, such as gravitino decay, extra dimensions, and dark photons. An overview of such models can be found in [3].

### 3.3 Antihelium sensitivity

Compared to antideuterons, antihelium nuclei will deposit more energy along their tracks, due to having twice the charge. The GAPS tracker is designed with a large dynamic range, and

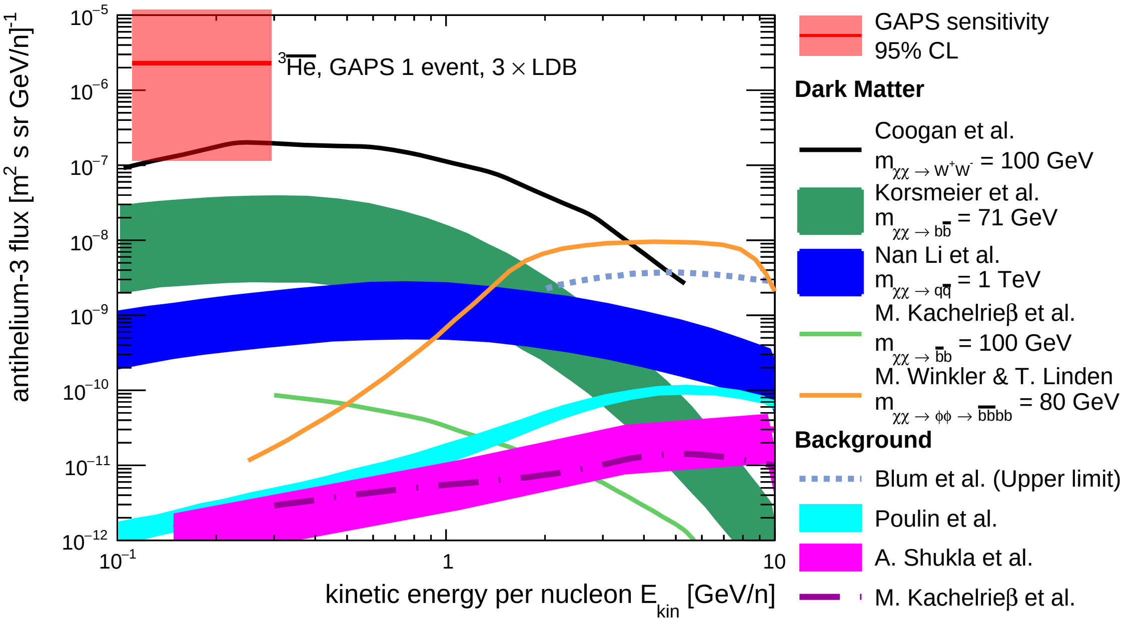

**Fig. 3:** The solid red line shows the single event sensitivity of GAPS to antihelium-3 nuclei (95% confidence level) for three LDB flights of 35 days each. The red box indicates the upper and lower bounds of the 95% confidence level. Also shown is the antihelium-3 flux predicted by a variety of dark matter [18–22] and standard astrophysical background [23–25] models. For theoretical predictions, the error bands illustrate uncertainties in the coalescence momentum but also include propagation uncertainties.

thus allows to precisely resolve the energy depositions along the primary track. Also, the higher multiplicity of the secondaries allows for good identification of the resulting annihilation star pattern. The antihelium analysis is conducted similarly to the antideuteron analysis [13]. The expected low astrophysical antihelium backgrounds allow for a strong sensitivity on the order of current dark matter models, as it is shown in Figure 3.

## 4 Conclusion

The GAPS experiment has the potential to expand our understanding of low-energy antinuclei in cosmic rays significantly: Its large acceptance, as well as its novel detection principle, providing sensitivity to antideuteron and antihelium fluxes, which are predicted by current dark matter models and extend the antiproton spectrum with a high statistics spectrum towards low energies. Its unique approach to antiparticle identification, using an exotic atom technique, will provide complimentary systematics to current experiments searching for cosmic antinuclei. The design phase of GAPS has been concluded, and the instrument has been integrated. GAPS has recently undergone extensive thermal-vacuum testing and is currently in its last integration and testing phase before its first flight in December 2024.

## References

[1] K. Freese, *Proceedings of 14th Marcel Grossman Meeting* **MG14 (2015)**

[2] M. Aguilar et al. *Physics Review Letters* **117** (2016) 091103.

[3] P.v. Doetinchem et al.,*Journal of Cosmology and Astroparticle Physics* **2020** (2020) 035.

[4] T. Aramaki et al. *Astropart.Phys.* **74** (2016) 6-13

[5] S. Feldman et al.,*This proceedings* .

[6] M. Manghisoni et al. *IEEE Trans.Nucl.Sci* **68** (2021) 11

[7] K. Perez et al., *Nucl. Instrum. Meth. A* **905** (2018) 12 [`1807.07912`].

[8] S. Okazaki et al., *Applied Thermal Engineering* **141** (2018) 20 .

[9] F. Rogers et al., *Astropart. Phys.* **145** (2023) 102791

[10] M. Xiao, A. Stoessl, B. Roach, C. Gerrity, I. Bouche et al. e-Print: 2305.00283 [physics.ins-det] **(2023)** .

[11] K. Abe et al.,*Phys. Rev. Lett.* **108** (2012) 131301.

[12] D. Gomez et al *PHys Rev. D***98** (2018) 023012.

[13] N. Saffold, T. Aramaki, R. Bird, M. Boezio, S. Boggs, V. Bonvicini et al., *Astroparticle Physics* **130** (2021) 102580.

[14] M. Aguilar et al. *Physics Reports***894** (2021) 1–116.

[15] S. Orito et al *Physical Review Letters***84** (2000) 1078–1081.

[16] K. Abe et al *Physics Review Letters***108** (2012) 051102.

[17] O. Adriani et al. *Soviet Journal of Experimental and Theoretical Physics Letters***96** (2013) 621–627.

[18] M. Korsmeier, F. Donato and N. Fornengo, *Physical Review D* **97** (2018) 103011.

[19] A. Coogan and S. Profumo, *Physical Review D* **96** (2017) 083020.

[20] K. Blum et al., *Physical Review D* **96** (2017) .

[21] Y.-C. Ding et al., *Journal of Cosmology and Astroparticle Physics* **2019** (2019) 004.

[22] M.W. Winkler and T. Linden, *Physical Review Letters* **126** (2021) .

[23] V. Poulin et al., *Physical Review D* **99** (2019) 023016 [`1808.08961`].

[24] M. Kachelrieß, S. Ostapchenko and J. Tjemsland, *Journal of Cosmology and Astroparticle Physics* **2020** (2020) 048.

[25] A. Shukla et al., *Physical Review D* **102** (2020) 063004.

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