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Antinuclei Signatures of Dark Matter and the GAPS Experiment

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GAPS is a long-duration balloon experiment designed to measure the flux of low-energy ($<$ 0.25 GeV/n) cosmic antinuclei as signatures of dark matter. Many well-motivated theories for dark matter predict annihilation or decay channels that can produce final state hadrons which may include antiprotons and antineutrons that may coalesce to form low-energy antideuterons or antihelium. The background for complex antinuclei from standard astrophysical sources is orders of magnitude below the predicted flux from viable dark matter candidates at the low-energy range for which GAPS is optimized. The GAPS instrument is currently assembled in Antarctica and stands ready for its first flight during the December 2025/January 2026 launch season. This proceeding will cover the anticipated science impact GAPS will have on the current landscape of cosmic antinuclei measurements as well as the instrument design and novel detection technique employed by the experiment.

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1. Introduction

GAPS will measure the antiproton flux in an unexplored low-energy range [1]; be the first experiment optimized for cosmic antideuterons, a “smoking gun” signature for new physics [2]; and deliver leading sensitivity to cosmic antihelium [3]. The GAPS instrument consists of a silicon tracker with 1111 custom Si(Li) detectors [4–6], cooled by a novel oscillating heat pipe thermal system [7], and surrounded on all sides by a large-area, precision timing plastic scintillator time-of-flight (TOF) and trigger system [8]. GAPS utilizes a novel antiparticle identification technique, in which an incident antinucleus is slowed and trapped by the tracker material, forming an exotic atom [9]. The incident particle $\mathrm{d}E/\mathrm{d}x$ and velocity, characteristic de-excitation X-rays, and subsequent nuclear annihilation products uniquely identify the incident antinucleus species. The exotic atom-based technique enables GAPS to have a larger acceptance compared to traditional magnetic spectrometer-based approaches to cosmic ray detection, allowing for GAPS to provide unprecedented sensitivities and high-statistics measurements to expand current dark matter searches.

The GAPS instrument was commissioned in Antarctica in late 2024 for launch in the December 2024/January 2025 season; however, launch was not possible due to unfavorable surface weather conditions and the shortest window of flight-condition stratospheric winds in decades. The GAPS team will return to launch the experiment in late 2025. An overview of the GAPS instrument and ground commissioning can be found in further proceedings for this conference; see A. Stoessl’s contribution. These proceedings focus on the anticipated scientific impact of the 3-flight program of GAPS.

2. GAPS Scientific Impact

Decades of observational evidence support the existence of a non-luminous matter that makes up 85% of the total mass of the universe, but the true nature of dark matter has yet to be discovered. Many theories favor a heavy (GeV–TeV range) non-baryonic dark matter particle that interacts only feebly with ordinary matter. The annihilation or decay of a cold, heavy dark matter particle through some Beyond-the-Standard-Model (BSM) process could produce final state hadrons, including proton/antiproton and neutron/antineutron pairs. The coalescence of an antiproton and antineutron from a dark matter particle could result in a detectable, low-energy antideuteron that could not be explained as a standard astrophysics signal, probing a variety of dark matter models that evade or complement collider, direct, or other indirect searches [10].

Although standard processes are capable of forming heavier antinuclei, the production of low-energy antinuclei is highly suppressed [11]. Antiparticles can be created from a collision between cosmic rays and the interstellar medium (ISM), but baryon number conservation results in a high energy threshold required to produce antibaryons. The high energy threshold for incident cosmic rays tends to disfavor low-energy antinuclei products, and the flux of cosmic rays also decreases with increasing energy, making the production process unlikely to happen. These factors disfavor low-energy astrophysical antideuteron and antihelium production, and consequently, the detection of a single low-energy antideuteron or antihelium could be considered a "smoking gun" signature of new physics.

Several anomalies in cosmic-ray measurements offer tantalizing possibilities for new physics. Gamma rays from the Galactic Center [12], positron [13, 14] and antiproton excesses [15] could be interpreted as dark matter, but other explanations of these excesses through standard astrophysical processes are also possible. Systematic uncertainties further make a dark matter interpretation of these excesses difficult. AMS-02 has also announced on the order of 10 candidate antihelium events from over 14 years of data collection [16]. These results have yet to be published in a peer-reviewed journal, but confirmation of this signal would indicate an exciting area of new physics, and an independent measurement of cosmic-ray antihelium is needed.

GAPS will launch for the first of three flights in December 2025. Flight 1 will validate the novel, exotic atom-based detection technique, provide the first precision low-energy antiproton spectrum, and deliver leading sensitivity to antideuterons from viable dark matter models. Flights 2 and 3 will open sensitivity to broader, more generic, dark matter models with antideuterons. All flights will provide leading sensitivity to low-energy cosmic antihelium nuclei. Details of the sensitivities and detection techniques of GAPS will be discussed in Section 3.

2.1 A Precision Antiproton Spectrum

GAPS, in each 35-day flight at a 37 km float altitude, is expected to measure an unprecedented 500 antiprotons in $<$ 0.25 GeV/n energy range [1]. Current leading measurements of low-energy cosmic antiprotons come from PAMELA and BESS-Polar II, which combined measured fewer than 50 antiprotons in the 0.17-0.23 GeV/n range [17, 18]. In addition to over an order of magnitude more statistics, GAPS is expected to extend sensitivities down to a lower energy range, $<$ 0.1 GeV/n. GAPS benefits from a larger acceptance due to its unique design and detection concept, discussed in Section 3.

From a standard astrophysics lens, a low-energy antiproton flux measurement will give new insight into Galactic and Heliospheric propagation as well as atmospheric effects. Additionally, many well-motivated theories of dark matter predict antiprotons as a byproduct of BSM physics. The AMS-02 measurement of cosmic-ray antiprotons were interpreted as having a potential excess in the 10–20 GeV range [15]. This measurement could be interpreted dark matter signature with estimates of a rest mass in the range of 10s to over 100 GeV; this is consistent with a range of models that also explain the Galactic Center gamma-ray excess, e.g. see [19–21]; however, the significance of the AMS-02 antiproton measurement as a dark matter signature faces significant challenges in the understanding of antiproton production cross sections and propagation parameters. Light ($<$ 30 GeV) dark matter particles as well as primordial black holes are potential sources of low-energy antiprotons, so the GAPS measurement will extend sensitivities to new models of dark matter.

Additionally, any model of dark matter that produces antideuterons or antihelium should produce antiprotons in high quantities, with each additional antinucleon suppressing coalescence probability by a factor of $>$ 1000. Any complex antinuclei signature must be consistent with the antiproton flux, and thus the antiproton measurement GAPS will provide can serve as a point of comparison for future heavier low-energy antinuclei searches. Figure 1 demonstrates the impact GAPS will have on the current antiproton flux landscape, extending sensitivity to a lower minimum energy range and delivering over an order of magnitude more statistics than previous experiments.

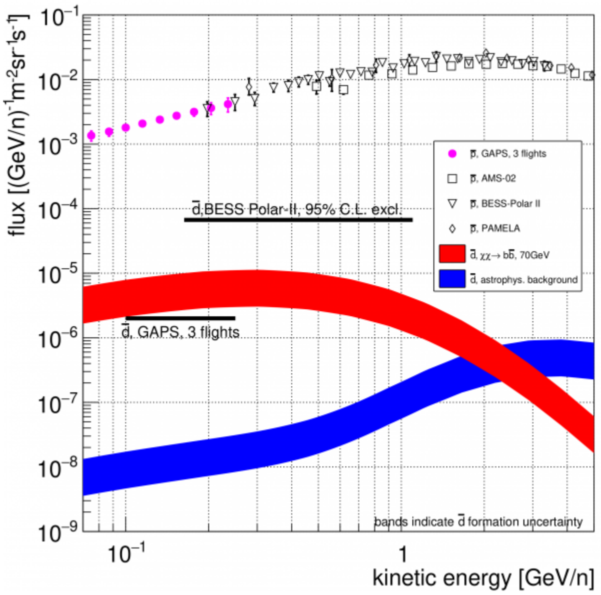

Figure 1: The expected antideuteron sensitivity of GAPS. Viable DM → $b\bar{b}$ model compared to the astrophysical background. Error bands indicate uncertainty in $\bar{d}$ production. Also included is the extended measurement of the antiproton flux in an unexplored energy region.

2.2 An Optimized Search for Antideuterons

Low-energy cosmic antideuterons have not yet been observed, but many viable dark matter models predict a low-energy antideuteron flux that is orders of magnitude higher than the astrophysical background [22]. A cold dark matter particle could annihilate or decay into partons or bosons, from which hadronic jets may form. Final state antiprotons and antineutrons are possible from such a process and could then coalesce to produce an antinucleus [23]. These combined processes can result in the formation of antideuterons from dark matter, but low-energy antideuteron production is highly suppressed for standard astrophysics as discussed earlier and the dark matter annihilation or decay happens essentially at rest by comparison [24].

There is still a wide parameter space for antideuteron-producing dark matter that is compatible with antiproton and gamma-ray measurements. Figure 1 shows the projected sensitivity of GAPS to antideuterons with a predicted flux from a generic 70 GeV WIMP-like dark matter annihilating into $b\bar{b}$ for comparison. Such a signal is predicted to exceed the astrophysical background by up to three orders of magnitude in the GAPS energy range. Through antideuterons, GAPS is sensitive to many viable dark matter candidates in addition to the generic WIMP model, for example decaying LSP gravitinos, ultra-heavy (5–20 TeV) WIMP models, hidden sector dark matter, primordial black holes, and others, e.g. see [25–27]. Even with conservative assumptions for coalescence and other uncertainties, a single detection of an antideuteron offers an extremely low-background signal of new physics. GAPS is uniquely optimized for the detection of low-energy antideuterons, providing sensitivity nearly two orders of magnitude better than the current leading limits by BESS-Polar II and extending sensitivity to a lower energy range [2].

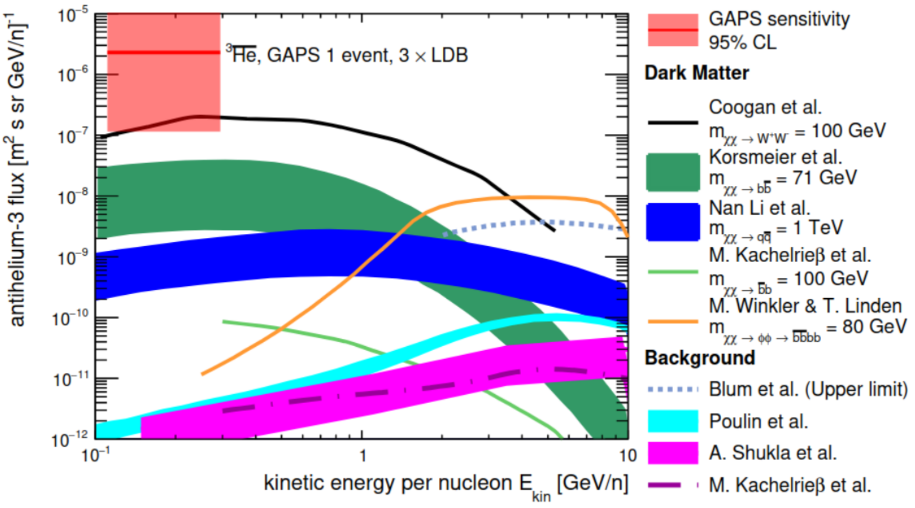

Figure 2: Predicted antihelium flux from a variety of dark matter and astrophysical models as well as the GAPS anticipated sensitivity (95% C.L. for three LDB flights). Error bands are due to propagation and coalescence uncertainties.

2.3 Novel Sensitivity to Antihelium

Antihelium-3 has gained interest as a potential signature of dark matter in light of the AMS-02 candidate events, and the possible origin of this signal has been the subject of numerous theories. Interpretations of these events include specifically-tuned models of dark matter annihilations [28, 29] or nearby antimatter clouds or even antistars [30]. GAPS, using a complementary detection technique to AMS-02, is the only current experiment that can independently test the existence of cosmic antihelium nuclei. Figure 2 depicts the current large uncertainties on possible dark matter and standard astrophysical antihelium production. GAPS is sensitive to antihelium in a lower energy range than AMS-02, where many models predict the contribution from new physics to be highest.

3. Novel GAPS Antinuclei Detection Technique

GAPS employs a novel, exotic atom-based detection method for low-energy antinuclei. The exotic atom approach was verified at the KEK antiproton beam [9, 31, 32]. Figure 3 (left) shows the entire GAPS instrument, assembled in Antarctica in late 2024. GAPS consists of two detector subsystems, a plastic scintillator time-of-flight (TOF) and trigger system and a multi-layer lithium-drifted silicon (Si(Li)) tracker. The TOF is responsible for triggering the readout of the entire instrument, optimizing the acceptance for interesting events like low-energy antinuclei, while also recording a low rate of standard cosmic-ray nuclei events. The tracker is responsible for measuring the trajectory of incident particles and also serves as a target to slow and capture antinuclei. The tracker is cooled to operating temperature of −40°C by an oscillating heat-pipe system coupled to a radiator, and the instrument is powered by a solar panel array.

The principle of identification of a low-energy antinucleus in GAPS is depicted in Figure 3 (right). An low-energy incident antinucleus passes through two TOF layers, where the TOF measures dE/dx, β, and position of the particle. The antinucleus loses energy through excitation

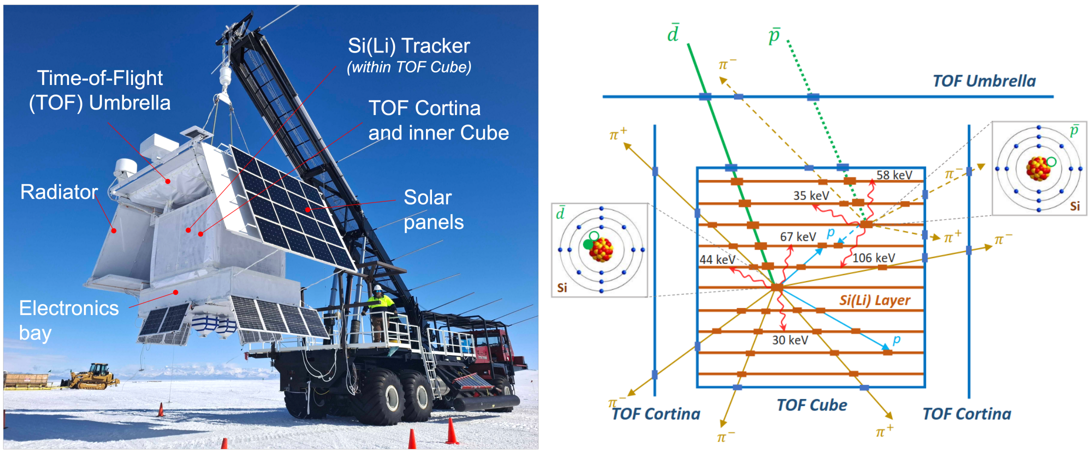

Figure 3: Left: The GAPS instrument, as commissioned in Antarctica in late 2024. The Si(Li) tracker is surrounded on all sides by the time-of-flight system. The instrument is powered by the solar array and the tracker is cooled by an oscillating heat pipe system connected to a large-area radiator. Right: Example of antinuclei identification in GAPS. An antideuteron and antiproton with similar velocities will have different stopping depth, dE/dx, characteristic X-ray energies, and multiplicity of annihilation products.

and ionization losses in the relatively thick (2.5 mm) Si(Li) detectors of the tracker, until it is slowed to a kinetic energy similar to the binding energy of the target atoms. The antinucleus then forms an exotic atom in an excited state with the target atom (which occurs with near unity probability). The unstable exotic atom de-excites through autoionizing transitions and radiation producing transitions, producing detectable X-rays with energies characteristic to the species of incident antinucleus [2, 3]. The antinucleus reaches a low shell and annihilates with the nucleus of the target atom, which produces a characteristic number of secondary hadrons. The Si(Li) detectors measure the energy depositions and trajectory of the incident antinucleus, as well as the deexcitation X-rays and nuclear annihilation products.

The exotic atom detection technique provides powerful rejection against cosmic-ray nuclei which, unlike antinuclei, cannot form exotic atoms. Additionally, GAPS is able to discriminate very effectively between different species of antinuclei using the combinations of incident β and energy depositions; multiplicities of annihilation products; and measured X-ray energies. GAPS features a higher acceptance in a lower energy range than traditional magnetic spectrometer-based cosmic ray detection techniques due to its exotic atom-based approach.

4. Conclusion

So far, it has been impossible to conclusively identify a dark matter signal in cosmic rays due to uncertain astrophysical backgrounds. The GAPS Antarctic balloon program is the first experiment optimized specifically for low-energy (< 0.25 GeV/n) antinuclei to find evidence of dark matter annihilation or decay. GAPS utilizes a novel approach to low-energy antinucleus identification which enables a large instrument acceptance, extending sensitivity to a range of viable dark matter models. The goal of GAPS is to deliver a first-time detection of or leading sensitivity to cosmic antideuterons, a signature of new physics essentially free of astrophysical background; a precision antiproton spectrum in an unexplored low-energy region; and leading sensitivity to cosmic antihelium.

GAPS stands ready to begin a baselined program of three flights over the coming decade. GAPS was commissioned in Antarctica in late 2024, following an extensive period of technological development and validation. Unfortunately, despite flight-readiness, the weather in that season was never adequate to ensure a successful flight. The GAPS instrument remains at the launch site, ensuring GAPS remains prepared for launch in this upcoming December 2025/January 2026 season.

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