Snowmass2021 - Letter of Interest

The GAPS Experiment:
Cosmic Antinuclei as Messengers for Dark Matter

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract:

Any dark matter signal in cosmic particle spectra continues to be obscured by large and uncertain astrophysical backgrounds. In the coming decade, the General Antiparticle Spectrometer (GAPS), which is the first experiment optimized specifically for low-energy ($<0.25\,\mathrm{GeV}/n$) cosmic antinuclei, will begin its Antarctic balloon program. Low-energy antideuterons provide a "smoking gun" signature of dark matter annihilation or decay, essentially free of astrophysical background. Low-energy antiprotons are a vital partner for this analysis, and low-energy antihelium could provide further discovery space for new physics. By opening unique sensitivity to low-energy antiprotons, antideuterons, and antihelium, GAPS is poised to offer a breakthrough in new physics searches using cosmic particles.

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The coming decade is an exciting time for searches for cosmic antinuclei, with experiments beginning to be sensitive to viable dark matter models. The General Antiparticle Spectrometer (GAPS[1;7;12], Figure 2) is the first experiment optimized specifically for low-energy ($< 0.25\,\mathrm{GeV}/n$) cosmic antiprotons, antideuterons, and antihelium as messengers of new physics[13;14]. GAPS is preparing for its initial Antarctic balloon flight in late 2022, with at least three flights anticipated in the coming decade. The novel GAPS particle identification technique is based on exotic atom capture and decay[12;15]. Compared to conventional magnetic spectrometers such as AMS-02, this design enables significantly larger instrument acceptance and higher background rejection power, which are key to rare signals searches such as the hunt for cosmic antideuterons or antihelium. Combined with the low geomagnetic cutoff of the Antarctic flight path, this novel design also opens sensitivity to an energy range below that of any other experiment.

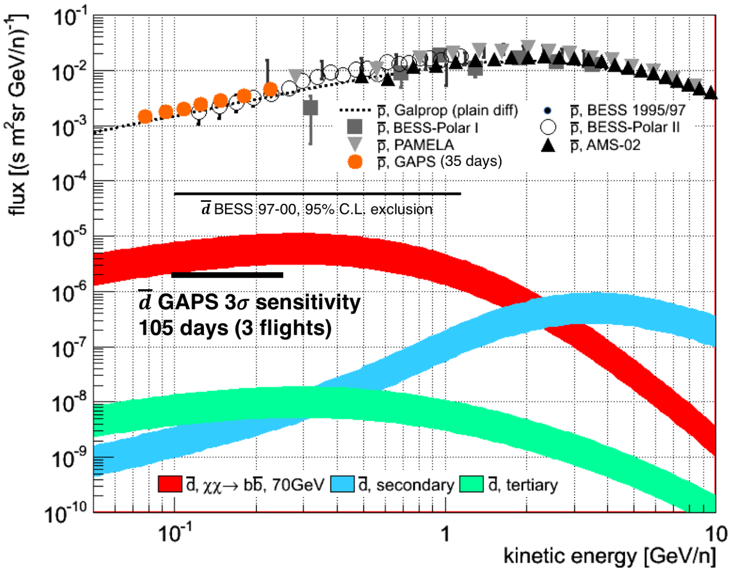

Figure 1: Predicted GAPS sensitivity to antiprotons (upper points) and antideuterons (lower bands) as a function of kinetic energy per nucleon. The anticipated GAPS antiproton measurement[1] after one flight is shown in comparison with the GALPROP plain diffusion prediction[2] and current spectra from AMS-02[3], BESS-Polar I/II[4;5], and PAMELA[6]. The anticipated GAPS 3σ antideuteron discovery sensitivity[7] after three flights is shown in comparison with the predicted flux from 70 GeV dark matter annihilating into $b\bar{b}$ (consistent with the AMS-02 antiproton and Fermi gamma-ray signals[8]), as well as the predicted secondary and tertiary astrophysical flux. The width of the predictions indicate uncertainty in coalescence momenta[9;10]. Conservative propagation models are assumed. The current best antideuteron limits are given by BESS[11]; the antideuteron sensitivity of AMS-02 in its final-magnet configuration has not been published, but will probe energies $>0.25\,\mathrm{GeV}/n$.

The unique strength of a search for low-energy antideuterons lies in their ultra-low astrophysical background[16–21]. Secondary or tertiary (background) antideuterons are produced by cosmic-ray protons or antiprotons impinging on the interstellar medium. This conventional production is extraordinarily suppressed, as the incident cosmic-ray spectrum is steeply falling with energy and high energies are needed to create both an antiproton and antineutron in these fixed-target collisions. Moreover, the kinematics of these collisions impair the production of antideuterons with low kinetic energy, so antideuterons below a few GeV/n are particularly rare.

A first-time detection of low-energy cosmic antideuterons would be an unambiguous signal of new physics, opening a new field of cosmic-ray research and probing a variety of dark matter models that evade or complement collider, direct, or other cosmic-ray searches. Figure 1 compares the astrophysical background to the flux expected from a standard WIMP, with mass and annihilation cross section that are consistent with both the reported low-energy antiproton excess observed in AMS-02 and and the Galactic center gamma-ray excess observed by Fermi[8]. This sensitivity extends to models of heavy WIMP (5-20 TeV)[22] and TeV-scale pure-Wino dark matter[23] with a Sommerfeld enhancement mechanism, which are motivated by the long-standing high-energy positron excess observed by PAMELA and AMS-02. Also shown is a Kaluza-Klein neutrino of extra-dimensional grand unified theories (LZP)[18], which is another example of non-supersymmetric dark matter. A decaying LSP gravitino,[24] which cannot be seen by direct detection experiments, would also produce a detectable flux. Of particular note, antideuterons explore hidden sector models, such as dark photons that evade direct detection and collider searches, via the hadronic decay of a massive mediator[25]. Antideuteron searches thus probe models of new physics over a wide mass range that cannot be resolved with other search methods.

The antideuteron formation and propagation have around one order of magnitude theoretical uncertainties.[14]. Upcoming accelerator-based experiments could give crucial constraints on models describing the formation of light (anti)nuclei in hadronic interactions[33;34], which are currently the dominant source of uncertainty. The uncertainty due to Galactic propagation spans the difference between the conservative MED and the optimistic MAX models.[35], with AMS-02 antiproton results favoring the MAX scenario[36]. Despite these large theoretical uncertainties, sensitive antideuteron searches will be able to definitively probe many dark matter scenarios.

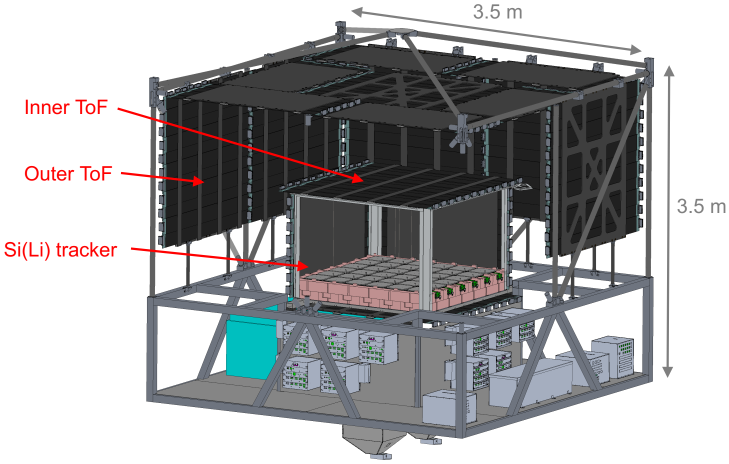

Figure 2: GAPS design, with a 10-layer (only two layers shown) array of 1440 Si(Li) detectors[26–31] surrounded by a large-area plastic scintillator time-of-flight system[32]. The novel GAPS antiparticle identification technique, based on exotic atom capture and decay, combines measurements of the incident particle time-of-flight, dE/dx, and total energy; exotic atom X-ray energies; and nuclear annihilation product particle multiplicity.

Low-energy antiproton measurements are an essential partner to these searches, as any antideuteron detection must be consistent with antiproton search results. As shown in Figure 1, GAPS will provide a precision antiproton spectrum in an unprecedented energy range below that of any other instrument. Since the antiproton spectrum from dark matter annihilations shifts towards lower energies with decreasing dark matter mass, precision measurements of the low-energy antiproton spectrum offer new phase space for probing light dark matter models and the existence of local primordial black holes[1]. Previous antiproton results from PAMELA[6;37], BESS[5], and AMS-02[3] have provided leading sensitivity to dark matter models, as well as astrophysical production and propagation scenarios[17;38–41]. The GAPS antiproton measurement will also be essential to understand the propagation of all charged particles in the Galactic and Solar environments. The comparison of low-energy antiproton fluxes from GAPS and AMS-02, during the same solar activity period and with different detection techniques, will reduce systematic uncertainties for future measurements.

Recently, the AMS-02 collaboration has announced the observation of several candidate antihelium-3 and antihelium-4 events[42–44]. Although antihelium arriving from antimatter-dominated regions of the universe is already nearly excluded[45;46], this announcement has prompted significant theoretical work on the implications for dark matter models[8;47–50] and light antinuclei formation[51;52], and it certainly further motivates the search for antideuterons. In the coming decade, confirmation or exclusion of an antihelium signal using the complementary detection technique of GAPS will be essential, given the transformative nature of such a claim.

The current generation of experiments sensitive to cosmic-ray antinuclei, including both GAPS and AMS-02, are discovery experiments. Successor experiments will need to measure spectra with high statistics. This is only possible with extended data taking and larger payloads. Therefore, the development of reliable ultra-long duration balloon platforms with low-geomagnetic cutoff trajectories will directly benefit the study of cosmic-ray antinuclei. At the same time, these flights serve as the technical proving ground for large-scale space-based experiments for cosmic rays, e.g., on the Moon's surface or at a Lagrange point.

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