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Dark matter identification with cosmic-ray antideuterons

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Abstract. Recent years have seen increased theoretical and experimental effort towards the first-ever detection of cosmic-ray antideuterons, in particular as an indirect signature of dark matter annihilation or decay. In contrast to indirect dark matter searches with positrons, antiprotons, or gamma-rays, which suffer from relatively high and uncertain astrophysical backgrounds, searches with antideuterons benefit from very suppressed conventional backgrounds, offering a potential breakthrough in unexplored phase space for dark matter. This report is a condensed summary of the article "Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuteron" [1].

1. Indirect dark matter search

The existence of dark matter is established on very different length scales from galaxies to galaxy clusters to the cosmic microwave background [2]. If dark matter was in thermal equilibrium in the early universe, and froze out when the temperature dropped due to expansion, it is a natural assumption that dark matter particles are able to interact with each other and produce Standard Model particles. Indirect searches exploit possible kinematic differences between the production of cosmic rays through dark matter and standard astrophysical processes to identify dark matter signals. Cosmic-ray antiparticles without primary astrophysical sources are ideal candidates for an indirect dark matter search, but recent results show that accomplishing this task with positrons and antiprotons is challenging due to high levels of secondary/tertiary astrophysical background. However, the latest results of major cosmic-ray instruments (e.g., AMS-02 [3]) for the positron fraction show evidence of a structure that might be interpreted as dark matter. Recently released AMS-02 antiproton-to-proton ratio data is inconclusive (e.g., [4, 5, 6]).

1.1. Antideuterons

Antideuterons may also be generated in dark matter annihilations or decays, offering a potential breakthrough in unexplored phase space for dark matter. The unique strength of a search for low-energy antideuterons lies in the ultra-low astrophysical background [1]. The dominant conventional sources for secondary (background) antideuteron production are cosmic-ray protons or antiprotons interacting with the interstellar medium [7]. However, the high threshold energy for antideuteron production and the steep energy spectrum of cosmic rays mean there are fewer particles with sufficient energy to produce secondary antideuterons, and those that are produced have relatively large kinetic energy.

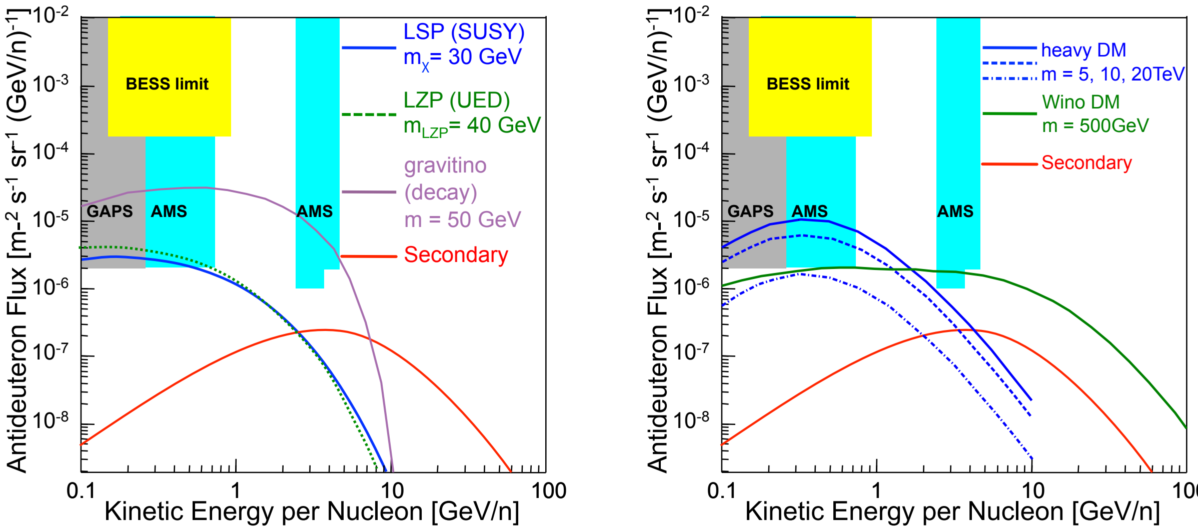

Figure 1. *Left)* Antideuteron limits from BESS [8], predicted antideuteron fluxes from different models [9, 10, 11, 12], sensitivities for AMS-02 for 5 years [13] and the planned GAPS experiments after three 35-day flights [14, 15]. *Right)* Predicted antideuteron flux for annihilation of dark matter with $m_{\rm DM} = 5$, 10, 20 TeV [16] (blue lines, top to bottom) into $b\bar{b}$ and from pure-Wino dark matter [18] (solid green line).

1.2. Discovery potential of dark matter searches with antideuterons

Many dark matter models with masses from $\mathcal{O}(1\,\rm GeV)$ to $\mathcal{O}(1\,\rm TeV)$ potentially produce an antideuteron flux that is within the reach of currently operating or planned experiments, AMS-02 and GAPS (Sec. 2). The left side of Fig. 1 shows the antideuteron flux expected from three benchmark dark matter scenarios. These dark matter candidates include a lightest supersymmetric particle (LSP) neutralino from the minimal supersymmetric standard model (MSSM), a 5D warped GUT Dirac neutrino (LZP), and an LSP gravitino. The expected secondary/tertiary background [12] is also shown. This figure reveals why low-energy antideuterons are such an important approach: the flux from a wide range of viable dark matter models exceeds the background flux by more than two orders of magnitude in the energy range below $0.25\,\rm GeV/\mathit{n}$, and by more than an order of magnitude up to $1\,\rm GeV/\mathit{n}$. However, antideuterons are not only sensitive to models with dark matter masses in the 10–100 GeV range, but also to heavy dark matter models with masses 0.5–20 TeV, motivated by the positron fraction excess [16]. These models require the MAX propagation model [17] and an enhanced annihilation cross section, such as provided by the Sommerfeld mechanism. The case for these multi-TeV mass particles annihilating into $b\bar{b}$ is shown on the right side of Fig. 1. The same figure also illustrates the case of heavy supersymmetric pure-Wino dark matter annihilating into W^+W^- [18].

It is vital to note that every process that produces antideuterons will also produce a much larger flux of antiprotons and any prospective antideuteron signature from dark matter is constrained by antiprotons. However, detecting deviations from the astrophysical antiproton flux requires very high statistics. Therefore, antideuterons provide an additional search channel with very strongly suppressed astrophysical backgrounds compared to antiprotons, and can also act as an essential probe to confirm or rule out potential deviations in the antiproton spectrum due to processes like dark matter annihilation or decay. On the other hand, a non-detection of a signal above background in the antiproton channel might also just be a consequence of experimental limitations and serves as additional motivation to pursue antideuteron searches.

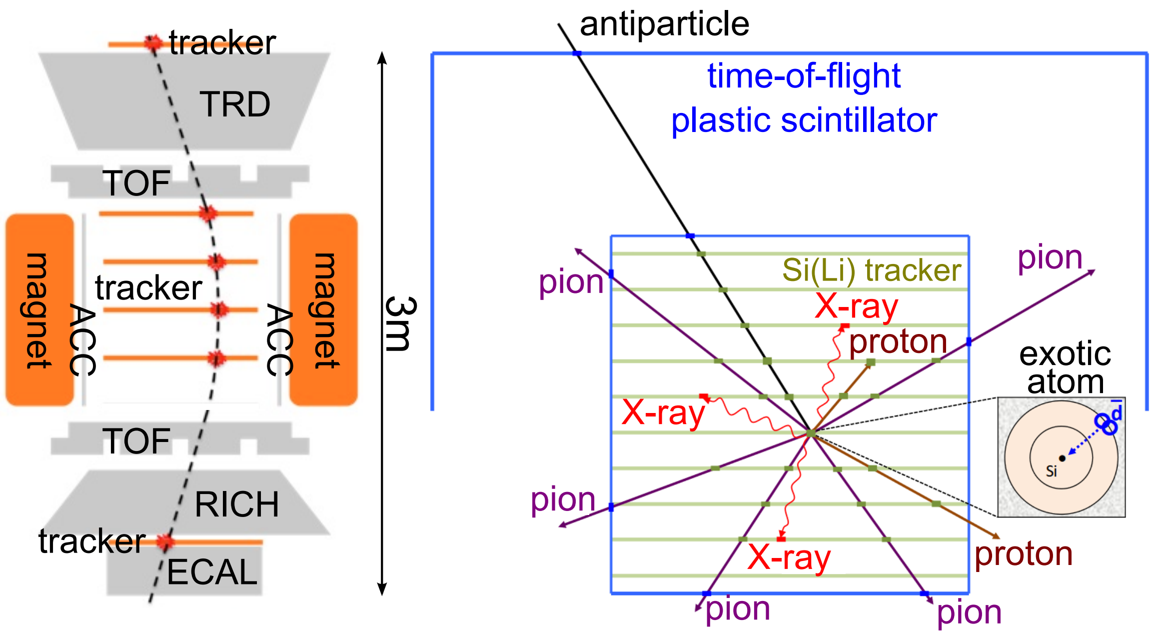

Figure 2. Layout of the AMS-02 (left) and GAPS (right) detectors.

1.3. Uncertainties for cosmic-ray antideuteron searches

The theoretical and experimental flux uncertainties for the antideuteron formation and propagation through the Galaxy are both on the order of $\mathcal{O}(10)$. Smaller uncertainties are introduced when antideuterons reach the solar system and are deflected by the solar magnetic field or suffer adiabatic energy losses in the solar wind. It is important to point out that the antideuteron fluxes presented here assume a conservative boost factor, due to dark matter clumps in the galactic halo, of $f = 1$. However, a boost factor of $f = 2$–3, as is consistent with current theoretical expectations, would increase dark matter fluxes by a factor f over those discussed below [9, 19]. Such a boost factor is only relevant for dark matter annihilation, as dark matter decay depends linearly on the dark matter density. In addition, the choice of the dark matter density distribution profile has only a small effect on the primary antideuteron flux and is not further discussed [20].

2. Experiments for the detection of cosmic-ray antideuterons

2.1. Experimental status

The absolute flux expected for antideuterons is very low, and thus any measurement attempt needs an exceptionally strong particle identification. The best existing antideuteron limits are given by the BESS experiment [8]. In the near future this search will exclusively rely on the Alpha Magnetic Spectrometer (AMS-02) [21], a multi-purpose cosmic-ray detector on the International Space Station (ISS), and the General AntiParticle Spectrometer (GAPS) [14], which is a dedicated low-energy antideuteron detector proposed to fly several times as a long duration balloon payload from Antarctica (Fig. 2). Fig. 1 shows that both experiments for the first reach time the sensitivity to probe the predictions of well-motivated dark matter models.

AMS-02 follows the principle of typical particle physics detectors, but shrunk to the size of the Space Shuttle payload bay. Particles are identified by analyzing the event signatures of different subsequent subdetectors (transition radiation detector, time-of-flight, anticoincidence counter, silicon tracker inside of a strong magnetic field, ring imaging Cherenkov counter, electromagnetic calorimeter). The GAPS detector will consist of ten planes of lithium-drifted silicon (Si(Li)) solid

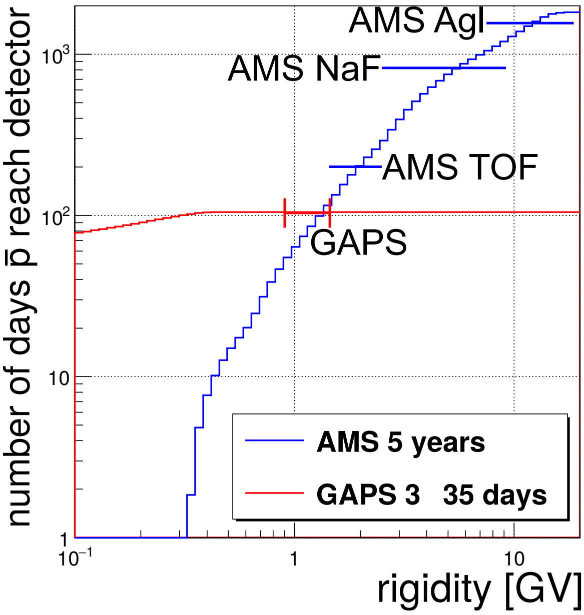

Figure 3. Simulated number of days as a function of rigidity antiprotons are able to reach AMS-02 and GAPS through the geomagnetic field (horizontal lines indicate the means for different rigidity regions).

state detectors and a surrounding time-of-flight system. The antideuterons will be slowed down in the Si(Li) material, replace a shell electron and form an excited exotic atom. The atom will be deexcited by characteristic X-ray transitions and will end its life by annihilation with the nucleus producing a characteristic number of protons and pions.

2.2. Experimental complementary

The use of multiple, complementary experiments has been successfully employed by the direct dark matter detection community. Separate experimental designs yield different backgrounds and approaches to suppressing these backgrounds, allowing for independent confirmation of any observed signal. As a rare event search, the hunt for cosmic-ray antideuterons requires a similar approach. If AMS-02 sees one or more antideuteron events a confirming experiment is absolutely needed. GAPS and AMS-02 have complementary energy ranges, but also some overlap at low energy, allowing the study of a large energy range for confirming signals and the best chance for controlling systematic effects. The key virtue comes from the different antideuteron identification techniques. AMS-02 and BESS rely on magnetic spectrometers, and thus face different backgrounds than the GAPS exotic atom approach. A magnetic spectrometer does not only have to deliver the isotopic separation between antideuterons and antiprotons, but also between the very abundant protons and antideuterons. Limited magnetic field strength and tracking resolution can cause protons to be misreconstructed with negative charge and antideuteron mass. In contrast, in the GAPS experiment low-energy protons are not able to fake the exotic-atom annihilation signature because protons cannot replace a shell electron nor annihilate with the nucleus. A critical benchmark to reduce systematic uncertainties of AMS-02 and GAPS will be the comparison of low-energy (anti)proton fluxes as well as antiproton-to-proton ratios.

AMS-02 orbits at relatively high geomagnetic cutoffs (Fig. 3), which reduces the number of detectable low-energy charged particles. By flying in Antarctica, the proposed GAPS trajectory is specifically tailored to low-energy particles, and thus GAPS will face a smaller geomagnetic cutoff correction. In addition, AMS-02 was launched at the beginning of the solar activity maximum. Although solar cycle 24 exhibits a relatively weak maximum compared to former cycles, a first GAPS flight would presumably happen during the next solar activity minimum [22], easing the uncertainties associated with low-energy measurements.

Therefore, the combination of AMS-02 and GAPS antideuteron searches is highly desirable. Unless GAPS is begun soon, confirmation of AMS-02 results would be a long while forthcoming. Similarly, a non-detection by AMS-02 may simply mean that the high background in the AMS-02 orbit and the difficulty of rejecting backgrounds are indicative not of the absence of antideuterons, but of the presence of high background.

3. Conclusions

This summary is based on the outcomes of the "$\bar{\mathrm{d}}$14 – 1$^{\mathrm{st}}$ dedicated cosmic-ray antideuteron workshop" and reviewed the status of cosmic-ray antideuteron searches for the identification of dark matter. Recent years have seen a lot of progress and antideuterons might offer a potential breakthrough in unexplored phase space.

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