

An indirect search for dark matter using antideuterons: the GAPS experiment

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Abstract. The general antiparticle spectrometer (GAPS) experiment is an indirect dark matter search. GAPS detects the antideuterons produced in WIMP–WIMP annihilation, a generic feature in many theories beyond the Standard Model. Antideuterons are a nearly background free signature of exotic physics. GAPS has substantial discovery potential for dark matter within the minimal supersymmetric model and its extensions, and models with universal extra dimensions. GAPS complements underground experiments, reaching parts of supersymmetric parameter space unavailable to them, and working to better constrain the properties of dark matter where they overlap in parameter space. GAPS is designed to be launched from a balloon. GAPS is funded for a prototype flight in 2011, to be followed by a long duration balloon flight to execute its science program. We discuss recent theoretical investigations on antideuteron searches, and their implications for experiment design. We describe the GAPS experiment placing particular emphasis on recent investigations that represent technical or conceptual extensions of the original GAPS concept.

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1. Fundamentals of dark matter detection with antideuterons*1.1. Basic idea of antideuteron searches*

A number of years ago it was pointed out by Donato *et al* [1, 2] that the antideuterons produced in WIMP–WIMP annihilations (the ‘primary’ antideuterons) offered a potentially attractive signature for cold dark matter (CDM). The reason is that the spectrum of antideuterons is fairly flat over the 0.1–1 GeV n^{-1} energy band, while the ‘secondary’ antideuteron spectrum (those produced in cosmic-ray interactions in the interstellar medium) sharply drops with decreasing energy. Thus a search for low-energy antideuterons can have a very high signal (primary antideuterons) to background (secondary antideuterons) ratio. Indeed, the background was so low at ~ 0.1 GeV n^{-1} that one could legitimately describe an experiment as background free. An antideuteron search for dark matter (DM) represents a major improvement over the well-established approach of searching for the WIMP–WIMP annihilation antiprotons. These primary antiprotons have a spectral shape and magnitude virtually identical to the secondary antiproton background. Indeed, the available data from many experiments clearly established that the available antiproton data could be fit without any primary antiproton component [3].

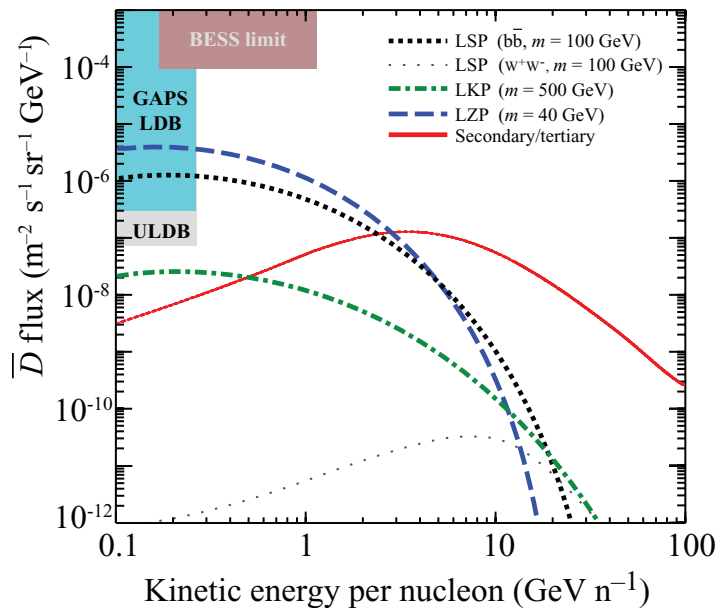


Figure 1. Sensitivity of BESS (current) and general antiparticle spectrometer (GAPS) antideuteron searches. The lightest supersymmetric particle (LSP), lightest Kaluza–Klein particle (LKP) and lightest Z_3 particle (LZP) are CDM candidates, as described in text (secondary/tertiary [4], primary [6]).

1.2. Modifications to the original antideuteron search idea

The strong scientific case for antideuteron searches for DM (section 2) has recently prompted more investigations of the crucial low-energy antideuteron background. It has been noted that several processes not previously envisioned contribute substantially to the low-energy antideuteron background [4]. In addition to the well-known secondary process $pA \rightarrow \bar{d}X$ must be added the $\bar{p}A \rightarrow \bar{d}X$ reaction (the ‘A’ is primarily a proton or helium nucleus). The latter is the dominant process because it requires only one nucleon–antinucleon pair ($\bar{n}n$), whereas the former requires two pairs ($\bar{n}n\bar{p}p$). The $\bar{p}A$ reaction is centered on much lower energies for kinematic reasons, and thus is a crucial contributor to the low-energy, secondary antideuteron flux. Another important process was recognized that also increases the low-energy background. These are the tertiary antideuterons. Tertiary antideuterons do not represent a new mode of antideuteron production, but rather a new mode of energy loss for secondary antideuterons. In particular it was noted that non-annihilating inelastic rescattering, $\bar{d}p \rightarrow \bar{d}X$, can result in substantial antideuteron energy loss. This ‘fills in’ the low-energy region of the antideuteron background spectrum. This analysis resulted in a many orders of magnitude increase in the antideuteron background at low energies. These results have been confirmed by more recent calculations as well [5] (hereafter DFM). A sample background is shown in red in figure 1.

1.3. Implications of the revised background for experimental searches

Since the Donato, Fornengo and Salati proposal there has been much discussion about the ‘smoking gun’, that is, identification of CDM by detection of a single antideuteron. Is this feasible? The answer to this question is a straightforward exercise in statistics given the

sensitivity of a given GAPS design, and the secondary/tertiary antideuteron spectrum. Our own calculations for the most current GAPS baseline (and longest feasible observation time on an ultra-long duration balloon) indicate that the one count threshold corresponds to roughly 99.5% confidence in detection of a primary antideuteron. This might very well be construed as detection of primary antideuterons with a single event. However the situation is a bit more complicated. One must properly account not just for the secondary and tertiary antideuteron background, but do a detailed calculation of the probability of misidentifying any background as an antideuteron. Using our current best estimate of all sources of background, rejection factors and misidentification processes, the one count threshold corresponds to a 99% confidence detection of a primary antideuteron. Detection of two or more counts would constitute a >3 sigma detection of primaries.

In an interesting twist, Baer and Profumo [6] (hereafter BP05) have correctly noted that detection of a single antideuteron in a GAPS balloon experiment provides higher confidence detection of DM than the same detection on a satellite-based GAPS. The latter, unlike the former, is sensitive enough to detect secondary and tertiary antideuterons, and thus cannot claim detection of DM with a single antideuteron. A satellite GAPS might still detect DM, with sufficient counts, by spectrally fitting the signal and background—which have different shapes. This is unnecessary in the balloon GAPS, where total counts alone is sufficient to claim a primary antideuteron detection.

2. Antideuteron searches: the science case

2.1. Direct and indirect detection techniques

Several recent reviews echo a growing consensus that no single experiment can definitively detect DM [7, 8]. Rather, a range of experiments are required that yield a self-consistent picture of the candidate DM particle and its relevant mass and couplings. A more broad-based experimental approach is particularly crucial since theoretical prejudices can substantially alter interpretations of a given data set. Gondolo [9] has driven this point home in the case of the DAMA results, where comparisons with upper limits from other experiments are complicated by the need for theoretical assumptions about WIMP mass, halo model and the nature of the coupling to the target scattering nucleus. In addition, direct detection is not without complications; the issue of elastic neutron scattering—a process that can mimic the WIMP signature—is a continuing challenge for direct detection [10].

As pointed out in the above reviews, what is required is not only experimental confirmation from different direct detection experiments (e.g. DAMA, CDMS, XENON) but confirmation from entirely different kinds of signals, and those signals need to be explainable with a self-consistent set of WIMP parameters. In this regard, the rich variety of indirect DM detection techniques is a valuable complement to the underground experiments. Because WIMP–WIMP annihilation is a fairly generic feature in beyond Standard Model physics, there are many signatures available. These include antiprotons (whose problems were discussed above), antideuterons, positrons, neutrinos and gamma rays. However few of these emanations meet Gondolo's [9] gold standard of having a signature due to WIMPS and nothing else. Galactic observations by EGRET [11, 12] and INTEGRAL [13] have detected excesses in diffuse high-energy gamma rays and 511 keV gamma rays, respectively. However both these excesses potentially have prosaic explanations; positrons (and hence 511 keV gamma rays) are

ubiquitous in astrophysical sources, and the diffuse gamma ray background (even without a DM component) is poorly understood. Thus, it is difficult to see how bumps or enhancements in astrophysical backgrounds could ever stand as independent evidence of DM. The exception might be a significant gamma ray line feature arising at very high energies, where there is no clear means of astrophysical generation. These can be detected from both long running Cerenkov telescopes such as MAGIC, CANGAROO II and HEGRA [14], more recently commissioned ones such as VERITAS [15] and HESS [14], and future ones such as CTA and AGIS [16]. In addition the space-based mission Fermi [17] is searching for such gamma ray line features over its energy band.

The difficulty of identifying DM associated features in astrophysical backgrounds is illustrated by very recent work on high-energy electrons and positrons. The HEAT positron bump [18] in the 6–10 GeV range was not confirmed by recent PAMELA results [19]. But PAMELA did detect a very significant rise in the positron fraction between ~ 10 and 100 GeV. This lends credence to recent results from PPB-BETS [20] and ATIC [21], both of which see a prominent electron feature in the ~ 400 GeV region. The feature admits an interpretation in terms of DM production of electrons and positrons. However recently reported Fermi observations [17] do not see this prominent feature, but rather a small deviation from a continuum spectrum, perhaps due to a nearby astrophysical source. The various measurements await reconciliation. Nevertheless, having a plethora of indirect approaches, even problematic ones, is potentially useful if a self-consistent picture across many experiments is to be achieved. Arkani-Hamed *et al* [22] have recently demonstrated that this is not entirely inconceivable even now, having reconciled DAMA with a number of ‘detections’ in indirect experiments within the context of a theory invoking a new force carrier in the dark sector.

2.2. Why antideuterons?

There are a variety of reasons to pursue antideuteron searches. Firstly, there is no experiment currently planned or operating that is dedicated to and optimized for high sensitivity antideuteron searches. Secondly, an antideuteron search is not easily confounded by its astrophysical background. Thirdly, a dedicated antideuteron search can have considerable experimental reach (discovery potential). And finally, an antideuteron search complements other direct and indirect search approaches. We discuss each of these points below.

2.3. The reach of antideuterons

BP05 [6] comprehensively investigated a GAPS antideuteron search and a more recent analysis has been done by DFM [5]. The latter updated the primary and secondary antideuteron flux calculation, and used a more sophisticated model to handle antideuteron transport. Both papers focused on WIMPS annihilating into $\bar{b}b$ pairs, since these give the largest yields among non-leptonic states, and because many bino-like configurations cover particularly interesting regions of minimal supergravity (mSUGRA). In addition BP05 looked at W^+W^- final states. They generally provide the lowest antideuteron signal among the non-leptonic final states. Within the framework of the MSSM this final state arises in several important scenarios involving wino-like and higgsino-like DM. The above approach allows the antideuteron flux to be bounded in a fairly model-independent fashion, useful for understanding the capabilities of antideuteron search experiments.

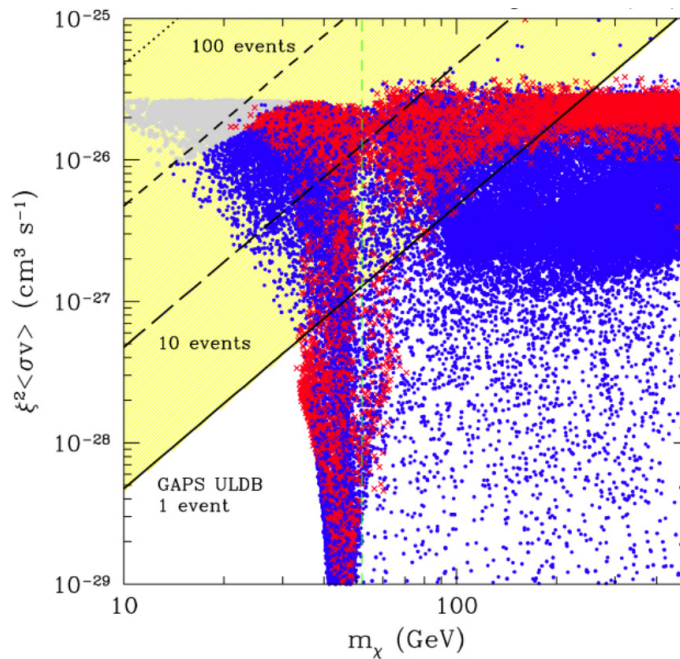


Figure 2. Sensitivity of a GAPS balloon experiment plotted in an effective annihilation cross-section neutralino mass plane for a low-energy supersymmetric model [5]. Models in red are consistent with WMAP CDM relic density.

Figure 1 shows the antideuteron flux from four different WIMP models (normalized to the background coalescence momentum) as a function of antideuteron kinetic energy. Also shown is the (only) upper limit on antideuterons, obtained with the BESS experiment [23]. GAPS will exceed the BESS upper limit by more than four orders of magnitude. Also note that for a neutralino in the $\bar{b}b$ decay mode, or for the LKP (the lightest particle in a 5-d warped GUT model), which at the ~ 40 GeV mass decays primarily through an s-channel resonance of the Z boson, an antideuteron signal is clearly detectable and at levels ~ 50 – 100 times the background. While not obvious in this plot, we note the LKP is easily detectable in the ~ 30 – 60 GeV mass range [6], and this is also the preferred mass range for an LKP consistent with the WMAP inferred CDM abundance. The LKP is not detectable with balloon GAPS. A satellite GAPS (not discussed further in this paper) might be able to detect the LKP through low-energy spectral fitting of the combined primary and secondary/tertiary antideuteron signal, but we have not yet studied this prospect. The W^+W^- decay channel provides a worse case, however the displayed neutralino is very heavy. At neutralino masses ~ 100 GeV, the antideuteron flux from the $\bar{b}b$ channel and the W^+W^- channel are comparable [6] and detectable.

Another example of the reach of antideuteron searches, parameterized in terms of the neutralino mass, is shown in figure 2 [5]. The $\gtrsim 50$ GeV neutralino masses are from a low-energy MSSM. The lower mass neutralino count rates originate in some non-universal gaugino models. GAPS can provide exceptional reach for probing such models, and very often in a region of SUSY parameter space consistent with the WMAP CDM relic density (red dots in figure 2). GAPS also accesses many regions of parameter space not consistent with the WMAP inferred CDM abundance. This is also true for many models relevant to antideuteron

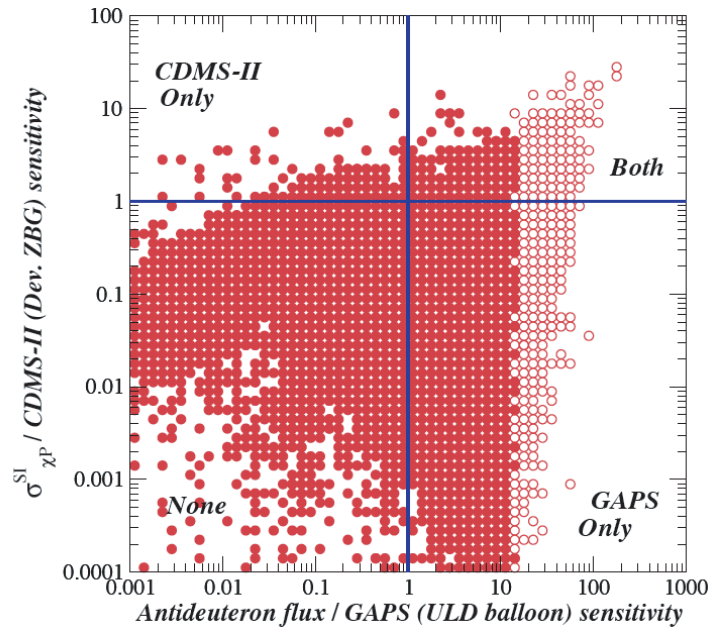


Figure 3. Quadrant plot of CDMS-II versus GAPS sensitivity. Red points indicate MSSM models consistent with WMAP relic abundance [6]. Horizontal line is a CDMS sensitivity and the vertical line is a GAPS sensitivity. Hollow circles are models already excluded by antiproton searches.

searches not shown here. As most recently emphasized in a paper by Kane and Watson [24], the relic density predicted for a given model of CDM depends on numerous assumptions that are not particularly natural. Relaxing these assumptions to include processes such as non-thermal production, entropy production after freeze-out, non-radiation-dominated expansion during DM production etc. should be considered. Thus considerable reach into the regions of parameter space excluded by the standard picture of thermal WIMP production and its corresponding relic CDM density is most important.

2.4. Antideuterons provide synergy with other search methods

We give some examples of how GAPS can work in synergy with other experiments as discussed extensively in BP05 [6] and Profumo and Ullio [25]. Figure 3 is a quadrant plot [6] of count rate in CDMS-II (shown as an interaction cross-section), representing a canonical direct detection experiment, and the flux in GAPS. This analysis is for a particular neutralino in the general MSSM, and is very restrictive. It only covers models giving the thermal relic abundance for CDM defined by the WMAP range. In the upper right-hand quadrant are models accessible to direct and antideuteron experiments. Within this region joint detection will provide better constraints on neutralino parameters than either technique alone. BP05 [6] emphasized the complementarity of direct and antideuteron searches. Many models not giving a large direct signal are detected by GAPS and vice versa. A similar quadrant plot and similar conclusions can be drawn comparing GAPS with IceCube [6], which searches for neutrino-generated muons. The neutrinos are produced in neutralino–neutralino annihilation in the Sun [26].

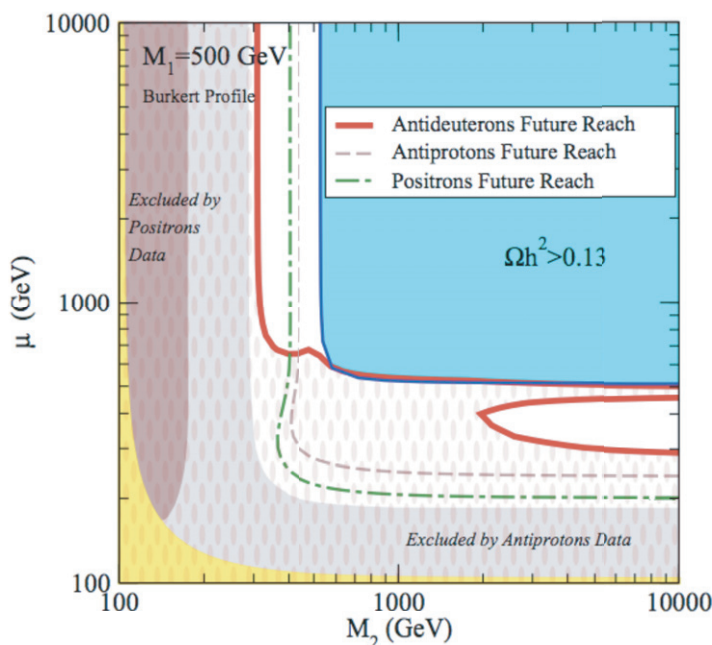


Figure 4. Search of split-SUSY parameter space illustrating how multiple experiments work together to better constrain the neutralino (LSP) properties [27]. The antideuteron future reach is for a satellite. A balloon experiment covers about 50% of the parameter space.

Split-SUSY models also illustrate how GAPS works in synergy with other experiments. Split-SUSY models are well studied, and perhaps most notable in that accelerator studies at LHC do not reach into the split-SUSY parameter space at all. Masiero, Profumo and Ullio [27] identified GAPS as an essential probe of split-SUSY, capable of covering large regions of parameter space available to no other method and acting in synergy with other methods to explore the entire parameter space. We illustrate the idea with the plot of figure 4. The antideuteron exclusion region, below and outside the red lines, encompasses the high M_2 , low to moderate μ parameter space (M_2 and μ are the gaugino and Higgs superfield parameters, respectively). Most of this space is unique discovery space to GAPS. However the low M_2 and low to high μ region are covered by a panoply of complementary techniques that together with GAPS fill in the entire parameter space. This plot uses a sensitivity for a GAPS satellite design, but a balloon-borne GAPS would cover about 50% of the antideuteron parameter space—a substantial reach into discovery space.

This section has concentrated on very generic models that are useful for bounding the capabilities of a GAPS antideuteron search, but more than 80 papers have been published analyzing antideuteron searches for specific beyond SM physics cases.

2.5. Predicted flux uncertainties in antideuteron searches

How well can one predict primary antideuteron fluxes, and thus constrain beyond SM physics? Several recent and comprehensive analyses [5, 6] address flux uncertainties and come to comparable conclusions. If galactic propagation models are exercised over their full parameter

range, the variation in predicted antideuteron flux can be as much as ~ 100 . Much of this uncertainty is associated with the value chosen for the diffusive halo thickness. However when this parameter is constrained to a more sensible range, not just any value that is allowed by the cosmic-ray abundance data, the uncertainty drops to about half to one order of magnitude [6]. With regards to the CDM halo modeling uncertainties, they are correlated with the diffusion model uncertainty. For propagation models with less extreme values of the diffusive halo thickness L , CDM halo modeling uncertainties drop to negligible levels for low-energy antideuteron searches such as GAPS. At higher antideuteron kinetic energy the CDM halo modeling uncertainty is larger. Following DFM [5], these results can be understood as follows. Antideuterons arrive from a volume characterized by the diffusive halo thickness L and a radius of order a few L centered on the Earth. For smaller values of L the antideuterons are arriving from a more local volume, and thus the exact details of the CDM halo distribution, especially details of its central cuspliness or precise core width, are not so important. For low-energy antideuterons the galactic wind uncertainty also enters, but it is a much smaller effect for not too small values of L . There is hope that PAMELA observations of cosmic-ray abundances will more tightly constrain the parameters of the propagation model.

Another factor that contributed to large uncertainty in BP05 [6] is boosting of the antideuteron flux due to clumpiness in the DM halo. However more recent analytic work, as well as high-resolution computer simulations resolving substructure in the inner DM halo, appear to have eliminated boost as a substantial source of uncertainty [28, 29]. Antimatter production boosts are typically $\sim 40\%$. Boosts $\gtrsim 10$ are obtained in only 1% of realizations—where a large subhalo is located near the solar system.

This leaves the nuclear physics uncertainty (mainly) associated with the formation of the antideuteron in the coalescence model. In this model an antideuteron forms when the antineutron–antiproton pair have a momentum difference less than a critical value, $2p_0$, where p_0 is the coalescence momentum. p_0 is constrained by hadronic production measurements, but there is a great deal of data, not all of it reliable, and some contradictory. Duperray *et al* [4] have conducted a critical reanalysis of all the available data relevant to the antideuteron production question. They greatly narrowed the acceptable range of p_0 , and subsequent reanalysis of the nuclear physics of antideuteron production [5] suggests that the overall uncertainty is then comparable to that from diffusion propagation.

A general conclusion we draw from all these analyses is that uncertainties associated with antideuteron flux predictions can likely be brought down to about the one and a half order of magnitude level. Thus despite primary antideuteron flux uncertainties, the antideuteron data, when combined with data from other experiments, should yield interesting constraints.

3. Approaches to antideuteron detection

There are two approaches to antideuteron detection. The first is with mass spectrometers utilizing superconducting magnets. These spectrometers are augmented with additional detectors for time of flight (TOF), discrimination of leptons and hadrons and calorimetry. The current upper limit on antideuteron flux by the BESS experiment utilized such an instrument, as does the AMS-02 experiment, scheduled for launch on the shuttle to the International Space Station. Magnetic spectrometers are not optimal for antideuteron searches at low energies. Their sensitivity is limited by the need for very large magnets. And they are challenged by a background due to misreconstructed deuteron and antiproton events. An ultra-long

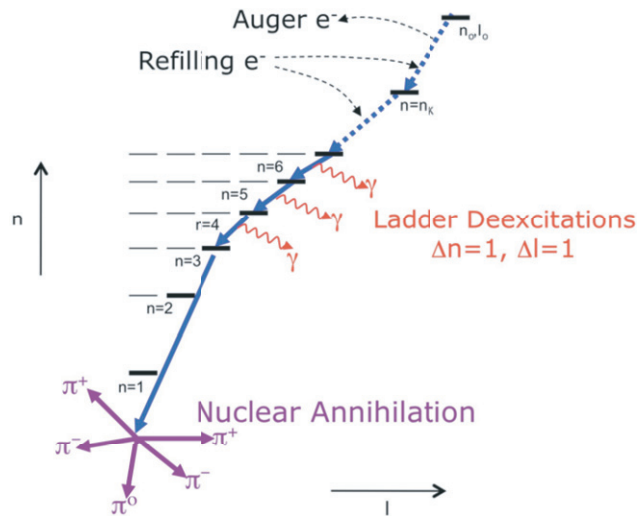


Figure 5. Sequence of deexcitations of an exotic atom leading to the characteristic radiation used to identify antimatter in the GAPS experiment [31].

duration balloon GAPS is $\sim 6\text{--}7$ times more sensitive than a multi-year AMS-02 search for antideuterons [5, 30]. Moreover AMS-02 operates in a higher energy band than GAPS, so its mean secondary/tertiary antideuteron background is $\sim 3\text{--}5$ times higher than GAPS. Nevertheless, GAPS and AMS-02 offer complementarity, since the AMS energy band extends from about the upper end of the GAPS band ($\sim 0.2 \text{ GeV n}^{-1}$) out to $\sim 1 \text{ GeV n}^{-1}$.

4. The GAPS concept

The GAPS approach is discussed in detail in Mori *et al* [31] (hereafter M02). We review the basic ideas here. The emphasis of further discussion will be to highlight new developments in the evolution of the GAPS concept. The GAPS concept is summarized in figure 5. An antiparticle that has been slowed down by the atmosphere passes through a TOF system (which measures particle velocity) and is slowed down by dE/dx losses in the target/detector. After stopping in the target, the antiparticle forms an exotic atom in an excited state with near unity probability. The exotic atom deexcites through both autoionizing and radiative transitions. Through proper target selection, the absorption of the antiparticles can be tailored to produce 3–4 x-rays in the cascade down to the ground state. Tailoring the x-rays to be $\sim 10\text{--}100 \text{ keV}$ allows for collection with standard x-ray detectors. After x-ray emission, the antiparticle annihilates in the nucleus producing a shower (star) of $\sim 5\text{--}10$ pions. The x-ray/pion emission occurs in less than a few nanoseconds. The x-ray energies that depend only on mass and charge, and are precisely known from quantum theory, uniquely identify the antiparticle. GAPS is ideally suited to low energy antideuteron searches because it is easy to range out low-energy ($\lesssim 0.2 \text{ GeV n}^{-1}$) particles.

The full particle identification—background rejection approach (illustrated for the most challenging case of antideuteron–antiproton) is shown in figure 6. In summary the process involves (i) simultaneous detection of x-rays emitted as the captured antiparticle makes atomic transitions from an excited state, (ii) TOF and depth sensing to distinguish heavier antideuterons

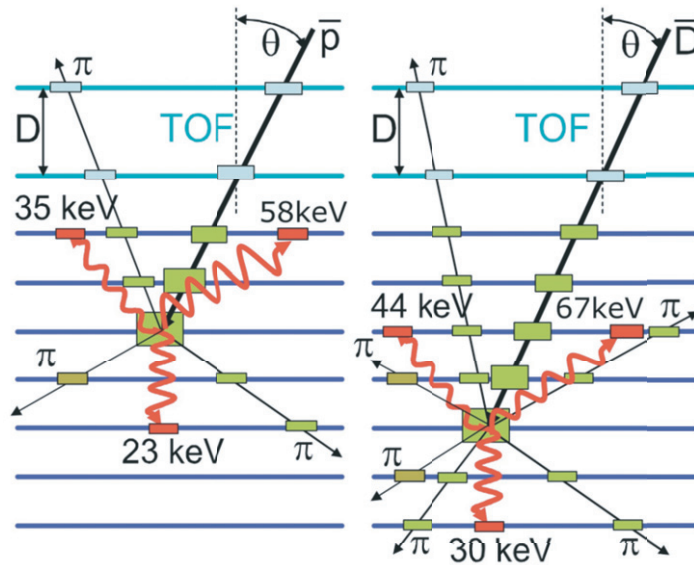


Figure 6. GAPS method of antiparticle identification. For the same measured TOF and angle (i.e. particle velocity), an antideuteron (right) will penetrate deeper, typically emit twice as many annihilation pions and emit x-rays of different well-defined energies than an antiproton (left).

from the lighter antiprotons and protons and (iii) multiplicity of pions emitted from nuclear annihilation—on average, roughly proportional to the antiparticle nucleon number.

5. Recent conceptual and technical advances in the development of GAPS

5.1. Evolution to Si(Li) detector planes

The heart of the GAPS instrument has recently changed to planes of Si(Li) detectors, a major departure from our earlier designs [31, 32]. That design involved a three-dimensional, cubic array of degraders, each cube surrounded by its own pixellated, alkali halide scintillator detector. The circular Si(Li) detectors, each with one-dimensional strip pixels, are hexagonally arrayed in a plane, and 13 of these crossed tracking planes of approximately $2\text{m} \times 2\text{m}$ forms the x-ray detector/degrader as well as a system capable of tracking particles. The new concept is illustrated in figure 7, which shows a view of the GAPS prototype experiment. The motivation to go to Si(Li) was prompted by a reanalysis of the required background rejection capability and the need to better distinguish antideuterons from antiprotons. The quality factor for rejecting temporally incoherent energy deposits (e.g. background x-rays uncorrelated with the antideuteron) scales like $(\tau \Delta E)^n$, where τ is the detector time resolution, ΔE the energy resolution and n the number of coincident atomic x-rays. Si(Li) detectors can provide a time–energy resolution product more than 20 times better than alkali halide scintillator crystals, and thus much better rejection. Similarly, the ability of the x-ray detector to distinguish antideuteron and antiprotonic x-rays depends on the energy resolution. A better energy resolution allows tighter energy cuts on the atomic lines, and thus less chance of confusing the antiparticle type.

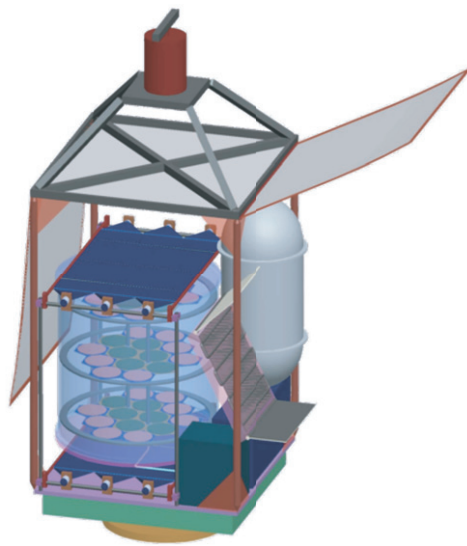


Figure 7. Schematic of GAPS balloon prototype. Hexagonally-arrayed Si(Li) detectors are visible in three tracking planes, as are the upper and lower sections of the TOF.

The Si(Li) planar geometry provides ample opportunity to fully exploit the pion stars for suppression of proton background, and to provide a vital additional capability for discriminating antiprotons and antideuterons. With a segmented TOF system providing velocity and incident angle and the Si(Li) planes providing tracking, antideuterons can be resolved from antiprotons/protons by stopping depth. The pixel size provides high enough resolution so that the probability of more than one x-ray or particle track in the same pixel is negligible. The low atomic weight of silicon also reduces internal background.

There is a two-fold advantage to Si(Li) not realized in our past designs. Relatively thin (2–3 mm), low Z targets such as Si(Li) have high escape fractions down to ~ 20 keV, well below the softest antideuteron x-ray. Thus Si(Li) can serve as both target and detector for antideuterons, simplifying design and maximizing x-ray detection efficiency. Secondly, combining the increased timing and energy resolution of the Si(Li) with the ability to suppress background and identify antideuterons by tracking pions and their multiplicity, permits us to utilize a ≥ 2 x-ray coincidence design rather than ≥ 3 x-ray coincidence of the original designs. This increases event detection efficiency and thus instrument sensitivity.

5.2. Identification and suppression of coherent x-ray backgrounds

A major impetus for improving the energy resolution of our detectors was further study of possible sources of energy deposits that can mimic atomic x-rays. Our previous work on this subject addressed temporally incoherent energy deposits (that is, not coincident with a charged-particle trigger from the TOF). They arise from absorbed and Compton-scattered atmospheric and cosmic-diffuse x-ray and gamma ray backgrounds, spallation and activation reactions in the payload, cosmic-ray-induced atmospheric neutrons and secondary neutrons and gamma rays (produced by cosmic-ray interactions in the payload) interacting in the x-ray detector. Our calculations of these processes are described in M02 [31]. Following accelerator testing of a

GAPS prototype at KEK in Japan [32, 33], we discovered a low level, temporally coherent (that is, occurring nearly simultaneously with the atomic x-rays) x-ray continuum background. It appears to arise in inner bremsstrahlung from the pion emission. Additional sources of coherent background were identified, including elastic scattering by cascade and evaporative neutrons emitted during nuclear annihilation and electromagnetic showers from neutral pions in the star. Suppression of the neutron scattering and inner bremsstrahlung background to tolerable levels was another major reason to move to the superior energy resolution of Si(Li).

5.3. Improved proton/antiproton discrimination

Protons and antiprotons can be confused with antideuterons when an appropriate TOF trigger combines with background x-rays or other energy deposits to mimic atomic x-rays from antideuterons. Even with modest time and energy resolution, protons can be suppressed with an appropriate high pion multiplicity threshold combined with depth discrimination. Antiprotons are then the primary source of confusion. Good suppression of the antiprotons requires not only the pion multiplicity and stopping depth signal, but the excellent timing and energy resolution of Si(Li). This is because the antiprotons, while much rarer (by $\sim 10^4$) than the protons, produce atomic x-rays. If one or more antiprotonic x-rays are misidentified in energy so that they are thought to be antideuteron x-rays, this may conspire with background x-rays or other energy deposits (e.g. elastic neutron scatters) to mimic an antideuteron signal. To fully suppress antiprotonic misidentification to levels comparable to the secondary and tertiary antideuteron background requires the Si(Li).

5.4. Exploiting other particles in the annihilation star

We are currently investigating an extremely promising approach, first mentioned in M02 [31] but never pursued, that could greatly augment the ability of GAPS to identify antideuterons and suppress backgrounds. The approach involves exploiting the multiplicity of fast ejectiles emitted in the nuclear annihilation. Fast ejectiles are energetic particle components consisting primarily of protons and neutrons, with a subdominant component of tritons, deuterons and kaons. The ejectile multiplicity, proportional to baryon number, offers excellent prospects for discrimination of antideuterons and antiprotons, and to even further suppress the possibility of misidentification of particles as antiparticles. The additional discriminatory power provided by this approach is substantial, and may even allow a mode where the atomic x-ray threshold can be set to ≥ 1 . In principle, this would allow us to increase sensitivity even further, although in practice we view this as a method of providing design margin on the sensitivity. This will be crucial as we grapple with all the details of the design of the science instrument in the next few years.

5.5. Si(Li) detector development

Si(Li) with good energy resolution (~ 2 keV FWHM) is now essential to GAPS. Moreover, we require some 1000+ detectors with a total mass ~ 200 kg. These detectors, of thickness ~ 2 – 3 mm and diameter 10 cm, will have eight conducting strips placed on one side for pixellation. Detectors of these specifications are primitive—they were first produced about 35 years ago [34]. The great challenge of these detectors is not performance—it is the enormous numbers that must be produced inexpensively and reliably. It is not feasible to produce Si(Li)

detectors at low enough cost per area in private industry. Large-scale fabrication will have to be done from scratch. We are therefore taking a two-pronged approach to the development of Si(Li) detectors.

Firstly, we are procuring a few Si(Li) detectors from Semikon Detector GmbH in Germany. These detectors range in thickness from 2.5 to 4 mm and should demonstrate performance appropriate for GAPS. These detectors will be evaluated to ensure they meet electronics noise, energy resolution, interelectrode capacitance etc. The noise must be compatible with the estimated in-flight operational temperature of -35 to -40 °C. Preliminary measurements of another Semikon detector, coupled with analysis of a preamplifier design, indicate that the target energy resolution is achievable at these temperatures. The detectors will arrive at this spring. We plan to order more Semikon detectors for the prototype flight if these detectors prove acceptable.

Simultaneously, we are proceeding with a program to fabricate Si(Li) detectors in-house. Once the process has been defined and verified, a dedicated facility will be constructed. The in-house development of flight quality detectors is expected to take several years, and several more years to produce the full complement for a science flight. The prototype flight from Japan in 2011 is baselined to have both Semikon detectors and detectors produced in our own facility. The approach to Si(Li) fabrication that we will pursue is less sophisticated than that of Semikon, and hews more closely to that of early work on Si(Li). We can tolerate a ‘low-tech’ fabrication approach because our required energy resolution (2 keV), pixel size (~ 1 cm strip) and minimum required x-ray energy (~ 10 keV) are so undemanding compared to the current state of the art. Thus our fabrication will utilize gold contacts on the p+ side rather than B-implantation, and diamond sawing to electrically define the n+ side pixels. The n+ side will be protected with a simple dielectric coating [35] to permit operation at flight altitude without a pressure vessel. We are currently preparing to fabricate our first detectors this summer. An Li-drifting station, to compensate for impurities in the silicon, has been fabricated and control software for the drifting is being written. More details of the Si(Li) development are forthcoming [36, 37].

5.6. Development plans

GAPS is funded for a prototype flight tentatively slated for 2011 from the new Japanese launch facility in Hokkaido, Japan. A science flight is slated for 2014. The date of the science flight is more driven by anticipated funding level and profile rather than technical considerations.

6. Conclusions

GAPS is an indirect DM search experiment. Its signature is primary antideuterons produced in WIMP–WIMP annihilations. The astrophysical background of antideuterons is extremely low. GAPS will complement current indirect and direct DM searches, and work in synergy with these other experiments to better constrain the properties of DM. The baseline detectors in the GAPS instrument have been changed to Si(Li), providing superior energy resolution. The improved energy resolution results in improved rejection of background events that can be misidentified as antideuterons. A prototype balloon instrument is scheduled for launch in 2011.

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