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Antideuterons as an indirect dark matter signature: Si(Li) detector development and a GAPS balloon mission

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Abstract

The General AntiParticle Spectrometer (GAPS) is a novel approach for indirect dark matter searches that exploits cosmic antideuterons. GAPS complements existing and planned direct dark matter searches as well as other indirect techniques, probing a different and unique region of parameter space in a variety of proposed dark matter models. The GAPS method involves capturing antiparticles into a target material with the subsequent formation of an excited exotic atom. The exotic atom decays with the emission of atomic X-rays and pions from the nuclear annihilation, which uniquely identifies the captured antiparticle. This technique has been verified through the accelerator testing at KEK in 2004 and 2005. The prototype flight is scheduled from Hokkaido, Japan in 2011, preparatory for a long duration balloon flight from the Antarctic in 2014.
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Keywords: Dark matter; Antiparticle; Antiproton; Antideuteron; Exotic atom; GAPS

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1. Introduction

WMAP results confirmed that 72% of our universe is dark energy and 23% is dark matter (Spergel et al., 2003; Komatsu et al., 2010). Many cosmological observations, such as galactic rotational curves and gravitational lensing, provide further evidence for the existence of dark matter and dark energy. The nature and origin of these phenomena, however, are still unknown. Many theories are proposed for dark matter and supersymmetry (SUSY) is considered one of the most promising. It postulates that all the particles in the standard model have superpartners. The neutralino could be the lightest SUSY particle (LSP) and one of the strongest candidates for dark matter in this theory. It is stable on cosmic time scales and interacts with matter very weakly. One of the remarkable properties of the neutralino is that it is a Majorana particle. It co-annihilates and produces particles, including electrons, positrons, gamma-rays, neutrinos, antiprotons, antideuterons, etc., which an indirect dark matter search could detect. The general antiparticle spectrometer (GAPS) is designed to search for antiparticles, especially focusing on low energy antideuterons (<0.3 GeV/n). As first noted by Donato et al. (2000), the low energy antideuteron production from the cosmic ray interactions (secondary flux) is kinematically restricted, while the neutralino annihilation (primary flux) produces the low energy antideuterons through hadronization and coalescence. Other dark matter candidates, such as the

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Kaluza–Klein particle (LKP) and the right-handed neutrino (LZP) in universal extra dimension (UED) theories, also produce low energy antideuterons, as seen in Fig. 1 (Baer and Profumo, 2005; Duperray et al., 2005). The BESS experiment made the first upper limit of antideuteron flux (Fuke et al., 2005) and GAPS will exceed the upper limit by more then 3 orders of magnitude. Furthermore, as seen in the quadrant plot (Fig. 2), a balloon-borne GAPS experiment from the Antarctic would be able to probe a different and unique region of SUSY parameter space compared with, for example, CDMS-II, and other underground direct dark matter experiments (Baer and Profumo, 2005). (The four quadrants are defined by the GAPS and the CDMS-II sensitivities.) There are more than a dozen operating or planned direct searches, which also probe quadrant II, while GAPS alone reaches into the discovery space of quadrant IV. In quadrant I, GAPS and underground experiments can work together, tightly constraining the properties of dark matter.

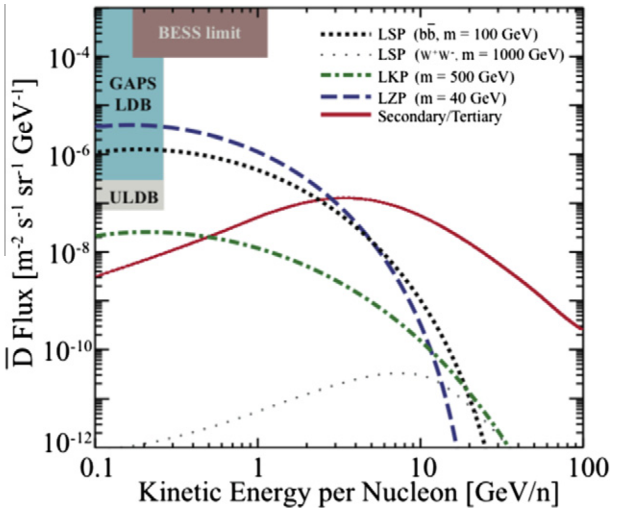

Fig. 1. Antideuteron flux at the top of the atmosphere, compared with GAPS sensitivity and BESS upper limit (Fuke et al., 2005). The blue dashed line (LZP), black dotted line (LSP), and green dot-dashed line (LKP) represent the primary antideuteron fluxes due to the dark matter annihilations (Baer and Profumo, 2005). The red solid line represents the secondary/tertiary flux due to the cosmic ray interactions (Duperray et al., 2005). (For interpretation of color mentioned in this figure the reader is referred to the web version of the article.)

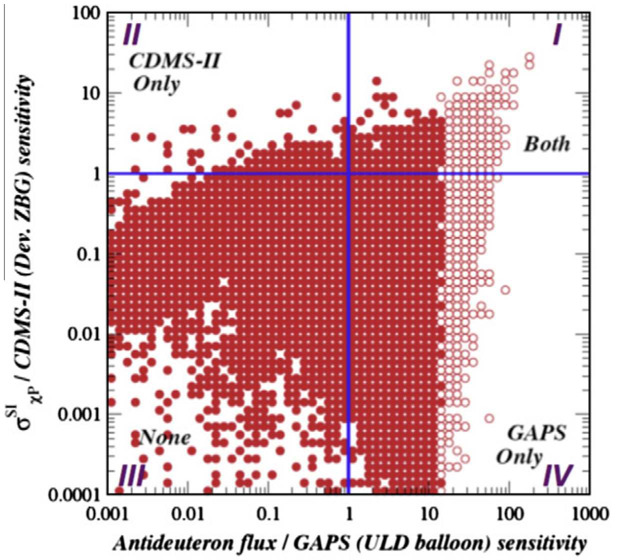

Fig. 2. Quadrant plot of the CDMS-II vs. GAPS sensitivity (Baer and Profumo, 2005). Red points are ensembles of SUSY models that are consistent with the thermal neutralino relic abundance in the WMAP range. Hollow circles are models already excluded by antiproton searches. *X*-axis is antideuteron flux normalized with GAPS ultra long duration balloon (ULCB) flight. The *Y*-axis is the neutralino-proton spin-independent scattering cross section normalized with the maximal sensitivity of the CDMS-II experiment. (For interpretation of color mentioned in this figure the reader is referred to the web version of the article.)

Updated calculations of antidueteron flux due to WIMP annihilation have been reported (Donato et al., 2008). Recently, several papers have discussed potentially detectable antideuteron fluxes from dark matter decay and heavy dark matter (Ibarra and Tran, 2009; Bräuninger and Cirelli, 2009). The implications for the GAPS experiment sensitivity are under study.

2. Detection concept

The GAPS detector is specifically designed for antiparticle detection through two simultaneous signatures; atomic X-rays and pions (Mori et al., 2002; Hailey et al., 2004; Hailey et al., 2006). A time of flight (TOF) system measures the velocity (energy) and angle of an incoming antiparticle. It slows down by the *dE*/*dx* energy loss and stops in the target material, forming an excited exotic atom with near unity probability. Through radiative transitions, it emits atomic X-rays as it de-excites. Here, the energy of the X-ray is strictly determined by the physics of the exotic atom. After the X-ray emission, the antiparticle annihilates in the nucleus producing a number of pions, which provides additional particle identification. X-ray yields from the exotic atom are well-known and we have measured antiprotonic X-ray yields with various targets at KEK in 2004 and 2005 (Hailey et al., 2006) (see Figs. 3–5).

One of the major background issues in this experiment is antiproton–antideuteron misidentification since antiprotons also emit both atomic X-rays and pions. With these 3 techniques, (1) depth sensing, (2) unique atomic X-rays, (3) pion multiplicity, we can sensitively distinguish antideuterons from antiprotons. Antiprotons with the same TOF stops sooner than antideuterons. The three highest antiprotonic atomic X-rays are different from the antideuteronic X-rays. An antideuteron produces roughly 4.5 charged pions in the nuclear annihilation, while an antiproton produces roughly 2.6 charged pions (Polster et al., 1995; Cugnon, 2002).

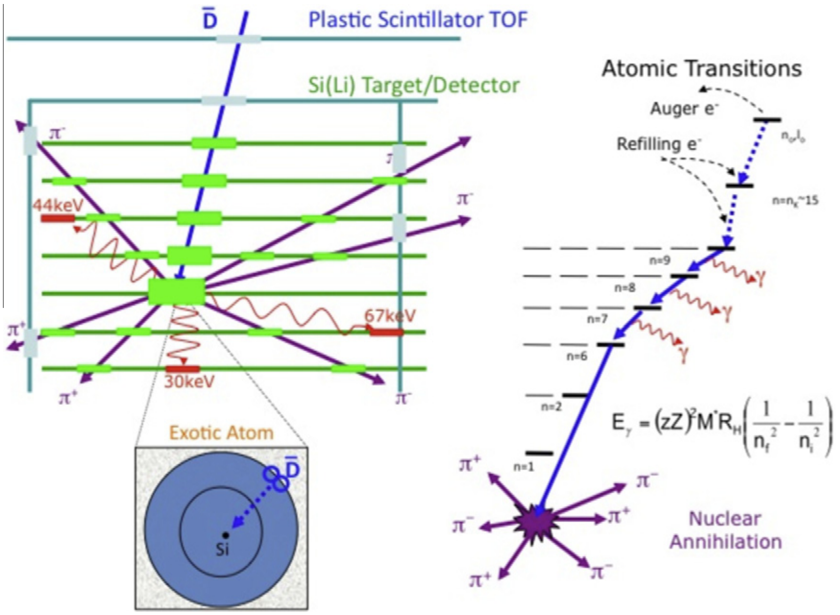

Fig. 3. GAPS detection concept. The antiparticle (1) slows down and stops in the target, (2) forms the excited exotic atom, (3) emits atomic X-rays as it de-excites, (4) produces pions in the nuclear annihilation.

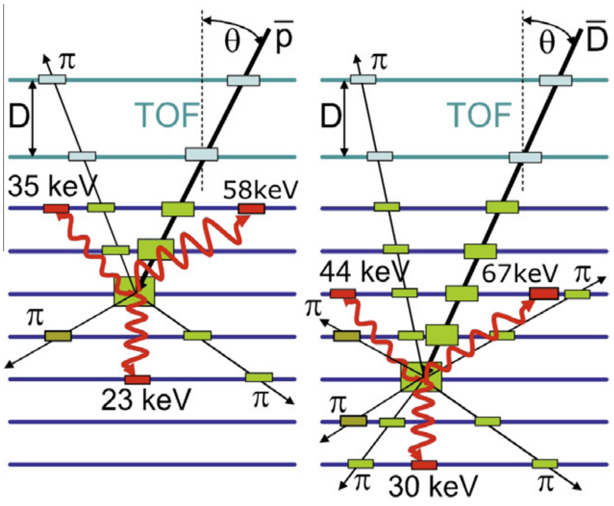

Fig. 4. Antideuteron–antiproton identification: (1) depth sensing, (2) unique atomic X-rays, (3) pion multiplicity.

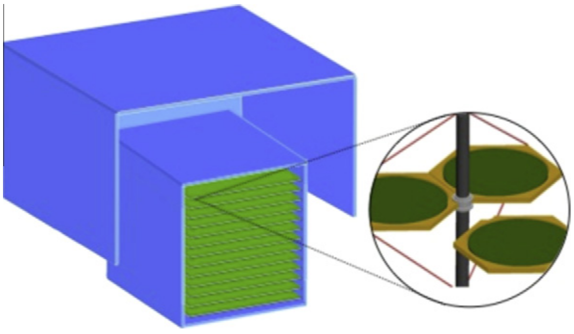

Fig. 5. GAPS detector design.

3. Detector design

The GAPS balloon flight has several unique features. It will be the first balloon flight with a very large pixellated lithium drifted silicon detector, Si(Li), surrounded by a very large TOF system without a pressure vessel. There will be 13 layers of detectors and each of them is composed of 4 inch diameter, 2.5 mm thick Si(Li) wafers. Since silicon is a relatively low *Z* material, it provides a good compromise between X-ray escape and detection. Each wafer is segmented into 8 strips providing for 3D tracking of the incoming antiparticle and outgoing charged particles. Our energy resolution requirement of 2 keV is modest for Si(Li), but sufficient to sensitively distinguish antideuteronic atomic X-rays from antiprotonic X-rays. The Si(Li) detector serves as both target and detector, which increases the detection efficiency (less dead volume).

4. Detector development

The GAPS prototype flight will install and test around 10 commercial and homemade Si(Li) detectors. The commercial detectors will be provided by SEMIKON and we have already received two detectors (Fig. 6). The performance including energy resolution, timing, detection efficiency and noise level is currently being evaluated and optimized. In the meantime, we have been developing homemade Si(Li) detectors with an in-house facility at Columbia University. The fabrication process for coarsely pixellated detectors is well-known. A schematic of the homemade detector is shown in Fig. 7 and the summary of the fabrication process is illustrated in Fig. 8.

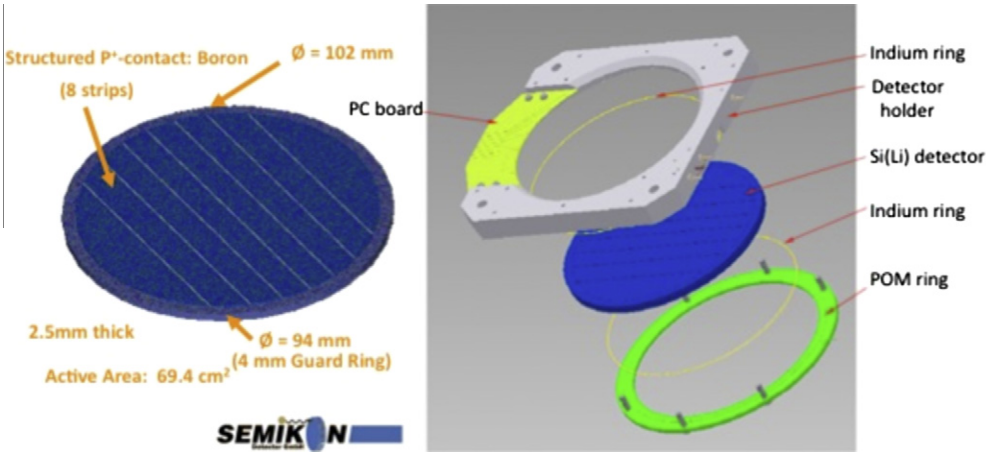

Fig. 6. Schematic of SEMIKON Si(Li) detector: boron is implanted on P^+ side, where 8 strips and a 4 mm guard ring are produced. The total active area is 70 cm^2.

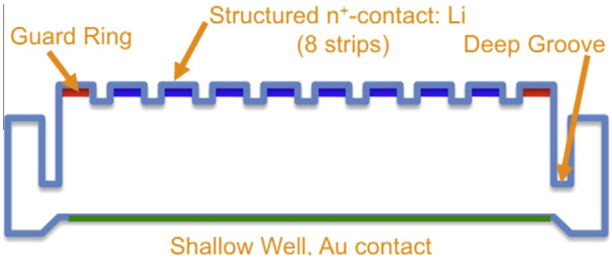

Fig. 7. Schematic of homemade Si(Li) detector: 4 inch diameter, 2.5 mm thick. Eight strips and guard ring at N^+ side.

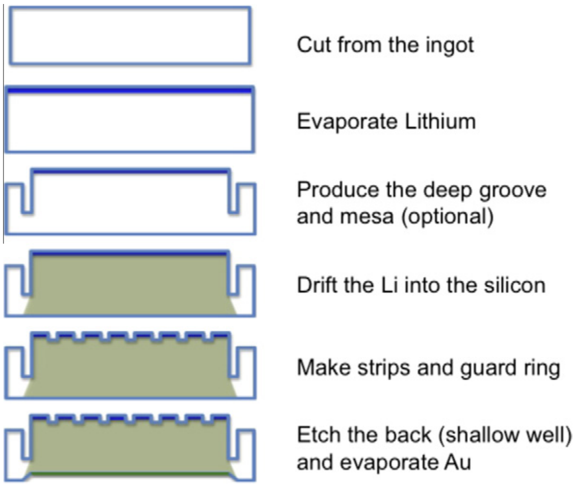

Fig. 8. Summary of Si(Li) fabrication procedure.

5. Future plan

The GAPS prototype flight is scheduled from Hokkaido, Japan in 2011. Stable, low noise Si(Li) detector performance including the cooling method, and the basic functionality of the TOF system will be demonstrated at flight altitude. We will measure the X-ray background and resolve the charged particle tracks in Si(Li) with the TOF trigger. The long duration balloon (LDB) flight from the Antarctic is planned for 2014 (see Fig. 9).

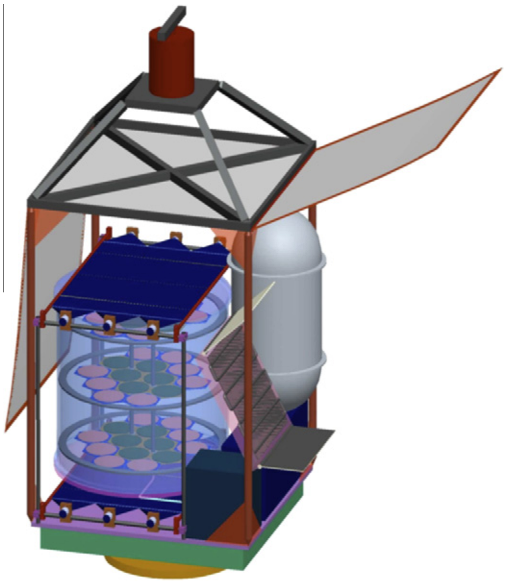

Fig. 9. Payload configuration image of GAPS prototype flight.

Acknowledgment

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References

Baer, H., Profumo, S. Low energy antideuterons: shedding light on dark matter. J. Cosmol. Astropart. Phys. 12, 008, 2005.

Bräuninger, C.B., Cirelli, M. Antideuterons from heavy dark matter. Phys. Lett. B 678, 20–31, 0904.1165, 2009.

Cugnon, J. Antideuteron annihilation on nuclei. Nucl. Phys. A 542, 559–578, 2002.

Donato, F., Fornengo, N., Salati, P. Antideuterons as a signature of supersymmetric dark matter. Phys. Rev. D 62, 043003, hep-ph/9904481, 2000.

Donato, F., Fornengo, N., Maurin, D. Antideuteron fluxes from dark matter annihilation in diffusion models. Phys. Rev. D 78, 043506, 2008.

Duperray, R., Baret, B., Maurin, D., et al. Flux of light antimatter nuclei near Earth, induced by cosmic-rays in the Galaxy and in the atmosphere. Phys. Rev. D 71, 083013, 2005.

Fuke, H., Maeno, T., Abe, K., et al. Search for cosmic-ray antideuterons. Phys. Rev. Lett. 95 081101, astro-ph/0504361, 2005.

Hailey, C.J., Craig, W.W., Harrison, F.A., et al. Development of the gaseous antiparticle spectrometer for space-based antimatter detection. Nucl. Instr. Meth. B 214, 122, astro-ph/0306589, 2004.

Hailey, C.J., Aramaki, T., Craig, W.W., et al. Accelerator testing of the general antiparticle spectrometer; a novel approach to indirect dark matter detection. J. Cosmol. Astropart. Phys. 0601, 007, astro-ph/0509587, 2006.

Ibarra, A., Tran, D. Antideuterons from dark matter decay. J. Cosmol. Astropart. Phys. 06, 004, 0904.1410v2, 2009.

Komatsu, E., Smith, K.M., Dunkley, J. et al. Seven-year Wilkinson Microwave Anisotropy Probe (WMAP) observations: cosmological Interpretation. arXiv:1001.4538, 2010.

Mori, K., Hailey, C.J., Baltz, E.A., et al. A novel antimatter detector based on X-ray deexcitation of exotic atoms. ApJ 566, 604, 2002.

Polster, D., Hilscher, H., Rossner, D., et al. Light particle emission induced by stopped antiprotons in nuclei: energy dissipation and neutron-to-proton ratio. Phys. Rev. C 51, 1167–1180, 1995.

Spergel, D.N., Verde, L., Peiris, H.V., et al. First-year Wilkinson Microwave Anisotropy Probe (WMAP) ovservations: determination of cosmological parameters. Astrophys. J. Suppl. Ser. 148, 175–194, 2003.