Antideuterons as an Indirect Dark Matter Signature: Design and Preparation for a Balloon-born GAPS Experiment

J. E. Koglin[1], T. Aramaki[1], S. E. Boggs[2], W. W. Craig[3], H. Fuke[4],F. Gahbauer[1,5], C. J. Hailey[1], N. Madden[1], K. Mori[1], R. A. Ong[6], T. Yoshida[4], H. T. Yu[1], and K. P. Ziock[7]

[1]Columbia Astrophysics Laboratory, Columbia University, New York, NY, USA
[2]Space Sciences Laboratory, University of California, Berkeley, CA, USA
[3]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), Sagamihara, Japan
[4]Lawrence Livermore National Laboratory, Livermore, CA, USA
[5]University of Latvia, Riga, Latvia
[6]Department of Physics and Astronomy, University of California, Los Angeles, CA, USA
[7]Oak Ridge National Laboratory, Oak Ridge, TN, USA

E-mail: koglin@astro.columbia.edu

Abstract. The General Antiparticle Spectrometer (GAPS) exploits low energy antideuterons produced in neutralino-neutralino annihilations as an indirect dark matter (DM) signature that is effectively free from background. When an antiparticle is captured by a target material, it forms an exotic atom in an excited state which quickly decays by emitting X-rays of precisely defined energy and a correlated pion signature from nuclear annihilation. We have successfully demonstrated the GAPS method in an accelerator environment and are currently planning a prototype flight from Japan for 2009. This will lead to a long duration balloon (LDB) mission that will complement existing and planned direct DM searches as well as other indirect techniques, probing a different, and often unique, region of parameter space in a variety of proposed DM models. Planes of coarsely pixellated Si(Li) detectors form the heart of the GAPS flight detector, providing both high X-ray energy resolution and good particle tracking. We will describe the proto-flight mission that will verify the performance of our Si(Li) detectors and cooling system in a flight-like configuration. We also will outline the LDB science payload design.

1. Introduction

Many extensions to the standard model predict weakly interacting, massive particles ('WIMPS') that are stable and thus ideal dark matter (DM) candidates. Underground direct detection experiments detect the nuclear recoil of WIMPS that scatter off target nuclei. WIMPS can also annihilate with other WIMPS in the galactic halo producing various debris such as gamma-rays, neutrinos, positrons, antiprotons and antideuterons. The General Antiparticle Spectrometer (GAPS) is specifically designed to uniquely identify low-energy, low-mass antiparticles which allows us to : execute deep searches for the WIMPS predicted by supersymmetric (SUSY) and universal extra dimension (UED) theories using antideuterons; search for evaporating primordial black holes using antideuterons, setting the best limits on primordial black hole density; and perform low energy cosmic-ray antiproton spectroscopy with several orders of magnitude better statistics than current satellite and balloon experiments. The detection rate for antideuterons yields direct information on the particle properties of the DM. When combined with observations from underground experiments, ground-based experiments such as VERITAS, space-based experiments such as GLAST and PAMELA, and accelerator-based experiments, an extremely comprehensive picture of the nature of DM can be obtained.

More than 80 recent papers discuss aspects of antideuteron DM searches. DM searches are highly model dependent, and there are lots of models! To illustrate the key features of a DM search with GAPS, the antideuteron flux expected from three different benchmark models calculated by Baer and Profumo [1] as representative of the most popular candidates for DM are plotted in Figure 1. GAPS is optimized for operation below 0.3 GeV/n, where the DM signal is largest. Also shown in the plot is the anticipated secondary and tertiary background of antideuterons [2]. Finally, Figure 1 shows the sensitivity to antideuterons for long-duration balloon (LDB) campaigns from Antarctica (60 days total over three flights) and the potential sensitivity from an ultra-long duration balloon (ULDB) flight (300 days total) that might be realized by our projected 2013 launch date. For comparison, the upper limit from the BESS experiment is also plotted. Figure 1 illustrates three important points: 1) GAPS is essentially a background free experiment; 2) GAPS has outstanding DM discovery potential for a wide variety of DM models, and 3) GAPS represents a major improvement over the state of the art.

2. GAPS Operating Principle

The goal of GAPS is to uniquely identify antiparticles using a method outlined in a 2002 concept paper [3]. An antiparticle that has been slowed 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

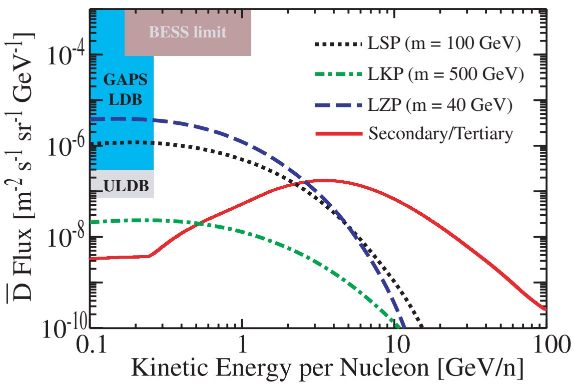

Figure 1. Benchmark models calculated by Baer and Profumo [1]: LSP (SUSY model, mediated primarily by $b\bar{b}$), LKP (Kaluza-Klein UED) and LZP (5D Warped GUT UED). The Secondary/Tertiary background from [2] and the reach of GAPS (for both LDB and ULDB missions) and BESS are also plotted.

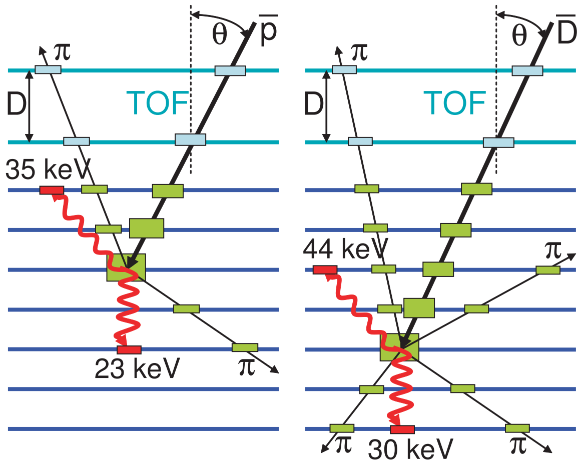

Figure 2. GAPS method of antiparticle identification. For the same measured TOF and angle, an antideuteron (right) will penetrate deeper, typically emit twice as many annihilation pions as well as emit X-rays of different energies than an antiproton (left).

near unity probability. The exotic atom de-excites through both autoionizing and radiative transitions. Through proper target selection, 3-4 X-rays detectable hard X-rays (i.e., in the range ∼10-100 keV) will be produced as the exotic atom de-excites down to the ground state. After X-ray emission, the antiparticle annihilates in the nucleus producing a pion shower (star) (∼5 pions per antiparticle nucleon). The X-ray/pion emission occurs within nanoseconds. In this way, GAPS relies on three techniques to uniquely identify antiparticles as illustrated in the cartoon in Figure 2: 1) time of flight (TOF) and depth sensing to distinguish heavier antideuterons from the lighter antiprotons and protons, 2) simultaneous detection of X-rays emitted as the captured antiparticle makes atomic transitions from an excited state, and 3) multiplicity of pions emitted from nuclear annihilation – on average, roughly proportional to the antiparticle nucleon number.

The X-ray energies, which depend only on mass and charge and are precisely known from quantum theory, uniquely identify the antiparticle. The simultaneous occurrence in a narrow time window of X-rays of the correct energies, along with a pion star, provide an enormously constraining signature with which to suppress background. GAPS is ideally suited to low energy antideuteron searches (<0.3 GeV/n), because it is easy to range out low energy particles. Our designs also allow large grasp compared to superconducting magnets. A GAPS prototype was tested at the KEK accelerator in Japan in 2004 and 2005 [4]. All open physics issues relevant to the design of a flight instrument, and amenable to ground-based testing, were resolved.

3. Balloon Experiment Design

GAPS is amenable to balloon-based experiments since the relevant science can be done with an instrument package of ∼1000 kg. We have designed a complete balloon-based GAPS experiment (bGAPS), as well as a prototype balloon experiment (pGAPS). The X-ray detectors are pixellated, high resolution Si(Li) produced from commercial 10 or 12.5 cm diameter wafers. The Si(Li) in bGAPS will be arrayed in a 13 layer tracking geometry, and each layer covers ∼2 m^2. The Si(Li) will be cooled to ∼-40C to provide low noise, high energy resolution performance. Groups of three Si(Li) will be mounted on the carriers and mechanically fixed to a central Al coupling through which a circulating cooling fluid will carry heat to a radiator panel facing away from the Sun. One-time, deployable shades will reduce the direct solar and albedo solar gain. The coolant temperature at the radiator is predicted by our thermal model to be -60C and -40C at the Si(Li) wafers. The detector planes will be surrounded by highly segmented plastic scintillator to provide the TOF trigger.

Using a smaller, three layer array of Si(Li) detectors, pGAPS will flight test all of the critical features of bGAPS. Through the pGAPS flight we will: confirm proper operation of the Si(Li) detectors at float altitude; measure X-ray and particle backgrounds of relevance to determining the overall instrument sensitivity; confirm the thermal model for predicting the Si(Li) operating temperature and verify the concept for cooling the Si(Li) detectors. The pGAPS experiment is anticipated to take place in late 2009 from Hokkaido, Japan.

4. Acknowledgments

This work was supported in part by NASA APRA grants NAG5-5393 and NNG06WC06G.

References

[1] Baer H and Profumo S 2005 *JCAP* **12** 8–+ (*Preprint* `arXiv:astro-ph/0510722`)
[2] Duperray R *et al.* 2005 *Phys. Rev.* **D71** 083013 (*Preprint* `astro-ph/0503544`)
[3] Mori K, Hailey C J, Baltz E A, Craig W W, Kamionkowski M, Serber W T and Ullio P 2002 *ApJ* **566** 604–616 (*Preprint* `arXiv:astro-ph/0109463`)
[4] Hailey C J, Aramaki T, Craig W W, Fabris L, Gahbauer F, Koglin J E, Madden N, Mori K, Yu H T and Ziock K P 2006 *JCAP* **1** 7–+ (*Preprint* `arXiv:astro-ph/0509587`)