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

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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. The GAPS method of using this combined X-ray and pion signature to uniquely identify antiparticles has been verified through accelerator testing of a prototype detector. We describe the design of a balloon-born GAPS experiment that complements 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. We also outline the steps that we are taking to build a GAPS instrument and execute multiple long duration balloon flights.

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 illustrates the key features of a DM search with bGAPS, the antideuteron flux expected from three different benchmark models calculated by Baer and Profumo [1] are plotted in Figure 1. Here, the LSP is associated with SUSY models (mediated primarily by $b\bar{b}$), and the LKP (Kaluza-Klein) and the LZP (5D Warped GUT) are associated with UED models. These three models are representative of the most popular candidates for DM. 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.

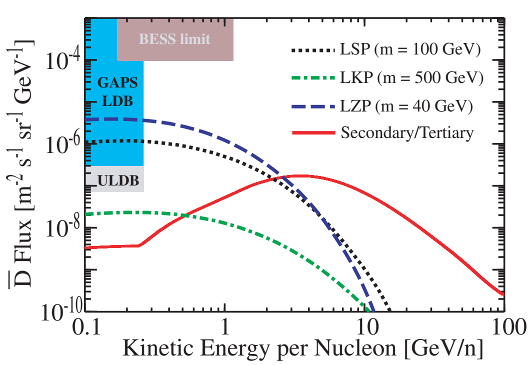

Figure 1: LSP, LKP and LZP search with bGAPS along with the Secondary/Tertiary background and the reach of bGAPS and BESS.

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 near unity probability. The exotic atom de-excites through both autoionizing and radiative transitions. Through proper target selection, the absorption of the antiparticle can be tailored to produce 3-4 X-rays in the cascade down to the ground state. Tailoring the X-rays to be ∼10-100 keV allows for collection with standard X-ray detectors. 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. Moreover 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.

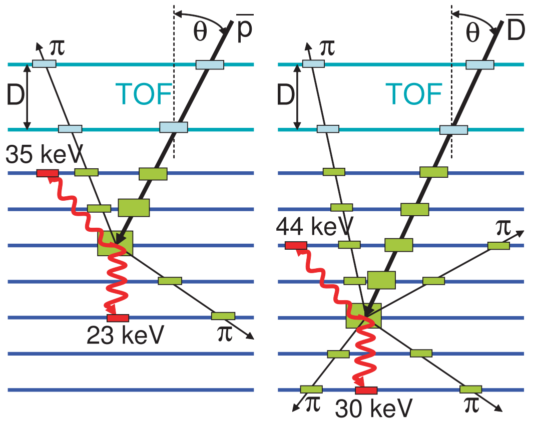

Figure 2: GAPS method of antiparticle identification. For the same measured TOF and angle (i.e., particle velocity), an antideuteron (right) will penetrate deeper, typically emit twice as many annihilation pions and emit X-rays of different well defined energies than an antiproton (left).

Accelerator Testing of GAPS Prototype

The pion tracking and depth-sensing techniques are well-understood from nuclear and particle physics experiments. Thus, our initial tests of the GAPS concept concentrated on the completely novel aspect of the project: detection of the de-excitation atomic X-rays to identify antiparticles. There is an enormous literature on exotic atoms in atomic and particle physics, but the exotic atom approach had not been exploited as a means of particle identification.

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. Gases were tested at KEK, as well as liquid and solid targets. The crucial parameter is the X-ray yield. Extensive measurements in kaonic and antiprotonic atoms give very high yields ($\sim$50%). We confirmed the validity of simple atomic physics models to scale from kaonic to antiprotonic atoms, and explicitly measured the X-ray yields in targets while resolving single antiproton event topologies. We also characterized internal and external instrument backgrounds relevant in predicting the flight performance of a GAPS instrument.

Balloon Experiment Design

GAPS is amenable to balloon-based experiments since the relevant science can be done with an instrument package of $\sim$1000 kg. We have designed a complete balloon-based GAPS experiment (bGAPS), as well as a prototype balloon experiment (pGAPS) shown in Figure 3. The pGAPS contains all the important features of bGAPS that must be flight tested. The X-ray detectors are pixellated, high resolution Si(Li) detectors. Pixellated Si(Li) detectors for detecting X-rays in the relevant GAPS band ($\sim$10-100 keV) have never previously been deployed in space. The Si(Li) detectors are 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 $\sim$2 m^2. pGAPS will flight test a smaller, three layers array of Si(Li) detectors.

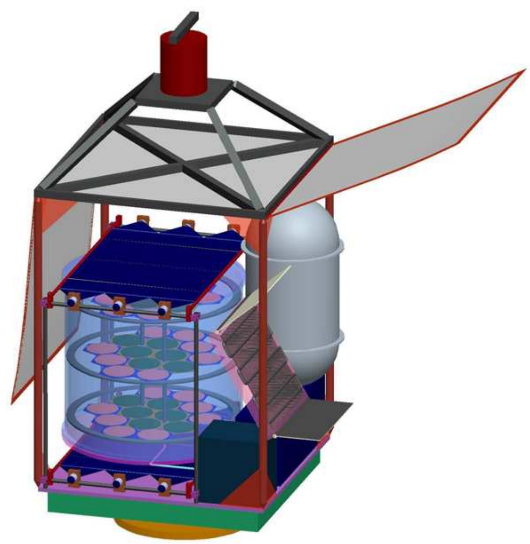

Figure 3: Prototype GAPS experiment (pGAPS).

The Si(Li) must be cooled to $\sim$-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 (c.v., Figure 4). The carriers are made of 0.030" Al sheet metal with stiffening flanges on the six sides. The coupling acts as both the structural support for this module and a single pass heat exchanger. A coolant port for 3M Novec heat transfer fluid is machined into this coupling for maximum turbulent flow mixing. These base units are connected vertically via the thermal coupling with thin-walled, lightweight carbon-fiber tubes (0.5" diameter). PTFE tubing is routed insided of the vertical carbon tubes and connect the thermal couplings. The coolant risers transfer the heat generated by the detector and ambient heat load. A modular sub-assembly includes six risers in an independent closed-loop cooling system. The coolant temperature at the radiator is predicted to be -60C and -40C at the Si(Li) wafers.

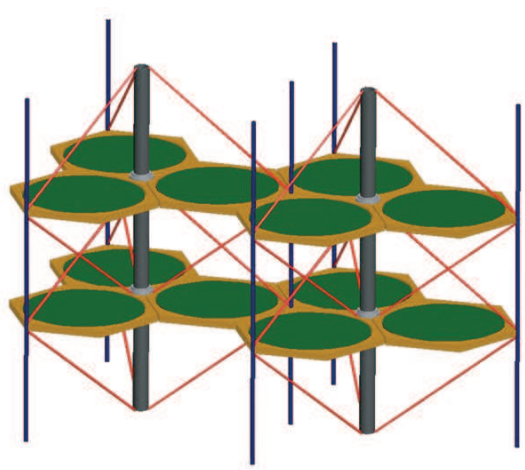

Figure 4: Illustration of four base units, two cooling tubes, six vertical supports and multiple cross supports.

A radiator panel system is required to remove the anticipated thermal load from the detector electronics and solar heat gain. One-time, deployable shades reduce the direct solar and albedo solar gain. These simple and lightweight shades are rolled thin aluminized Mylar sheet and thin coiled power springs that will unroll and support the mylar in the vacuum environment. A simple release mechanism deploys the shades at full altitude.

The goals of the pGAPS flight include: 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 Si(Li) operating temperature, and verify the concept for cooling the Si(Li) detectors. The first goal is particularly important since the Si(Li) detectors will be operated at float altitude without a pressure vessel. The Si(Li) utilizes a polyimid coating to passivate it and permit non-vacuum operation. This is the approach taken for the SIXA arrays on the Spectrum X-Gamma mission [5], but it is crucial to ensure the validity of the approach in a flight test before applying it to the thousands of detectors of bGAPS. In-flight measurements of X-ray background will help bolster our confidence in model predictions of the confusion rate – the number of background particle events accidentally mistaken for antideuterons. The pGAPS experiment is anticipated to take place in late 2009 from Hokkaido, Japan.

Acknowledgements

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