The General Antiparticle Spectrometer Experiment: Search for Dark Matter and Primordial Black Holes

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Abstract **– We discuss a new concept for the detection of antimatter. The general antiparticle spectrometer (GAPS) detects the X-rays and pions produced in the deexcitation and annihilation of an atom which has captured an antiparticle. The X-rays and pions are a unique signature of antimatter, and the X-rays identify the antiparticle type. GAPS is particularly effective at detecting antideuterons, which are produced in galactic dark matter interactions, and in the evaporation of primordial black holes. A balloon-based GAPS experiment represents a major new approach to the search for dark matter, and is the most sensitive method to search for primordial black holes.**

I. INTRODUCTION

One of NASA's four science goals is to "determine the origin, structure, evolution and destiny of the universe". To do this, the two towering problems that dominate the landscape of early 21st century physics must be solved: What is dark matter (DM) and what is dark energy? The current focus of our research addresses the first of these questions. The most popular theories of the origin of DM involve extensions of the "Standard Model" of particle physics. The most popular and physically well-motivated of these extensions are the supersymmetric (SUSY) theories and the universal extra dimension (UED) theories. Both classes of theories predict weakly interacting, massive particles ("WIMPS") which are stable. WIMPS are thus ideal candidates for the DM. WIMPS can directly scatter off nuclei, with the recoiling nucleus producing a detectable signal. This is the approach of the underground direct detection experiments. WIMPS can also annihilate with other WIMPS in the galactic halo. A byproduct of these annihilations are various debris such as gamma-rays, neutrinos, positrons, antiprotons and antideuterons. Near-term experiments exploiting this indirect detection approach to DM searches include GLAST and VERITAS (gamma-rays), AMANDA (neutrinos) and PAMELA (positrons).

Our work on GAPS[a] exploits indirect detection of DM through antideuterons: an extremely promising and unexplored approach [1]. The advantage of antideuterons is that they are essentially a background free, "smoking gun" signature of DM [2]. Detection of even a single antideuteron from space establishes the existence of galactic WIMPS, and provides constraints on parameters of SUSY and UED theories. One of the great attractions of a space-based antideuteron search is uniqueness; there are ~ thirty other operating or planned direct detection experiments. GAPS is more than a unique approach. The combination of detections/upper limits from underground experiments, GLAST and GAPS would provide much tighter constraints on the property of DM than any experiment alone. Moreover, for many of the embodiments of DM, GAPS alone is capable of detecting it (see below). The goal of our development efforts is a long or ultra-long duration balloon flight. There are three major areas of research upon which GAPS can have major impact. In particular GAPS can:

- execute deep searches for the WIMPS predicted by SUSY and UED theories using antideuterons; GAPS has as much chance as any current experiment to discover DM,
- 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.

II. CONCEPT OF OPERATION AND EXPERIMENT DETAILS

GAPS must distinguish antideuterons produced in WIMP annihilation from the more prosaic cosmic-ray debris including protons, heavier nuclei and antiprotons. The latter are produced in conventional proton-proton collisions in the interstellar medium. GAPS exploits the fact that antiparticles, when slowed down to very low velocities, can be captured by atoms. The combination of antiparticle-atom is called an "exotic" atom. The exotic atom is in an excited state, and it deexcites by a series of radiative transitions to the atomic ground state. During this deexcitation 3 or 4 X-rays are emitted, and the energy of the X-rays is precisely predicted by quantum theory, and is a unique signature of the mass of the antiparticle. When the antiparticle reaches the ground state it annihilates with the nucleus producing a burst of pions. The

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number of pions emitted (~4-8) can itself distinguish between antiprotons and antideuterons. The entire process of atomic X-ray and nuclear pion emission takes place in less than 10 nanoseconds. This is a unique signature, distinguishing both particle from antiparticle, and identifying the type of antiparticle.

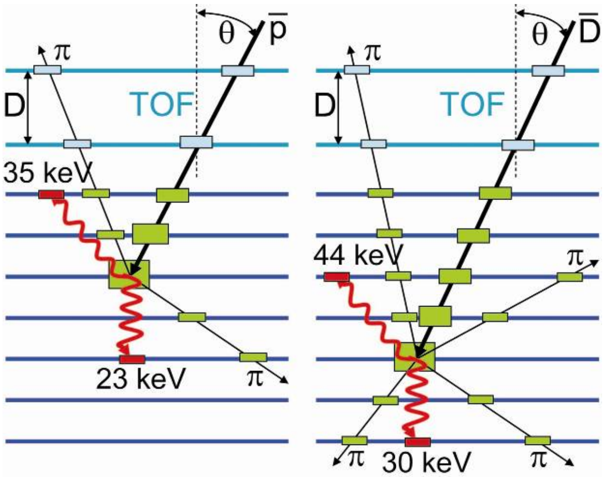

Fig. 1. GAPS method of antiparticle identification. For the same measured TOF and angle (i.e., particle velocity), an antideuteron (right) will penetrate deeper, typically emit twice as many annihilation pions and emit X-rays of different well defined energies than an antiproton (left).

Further discrimination between antideuterons, and the lower mass antiprotons and protons, is provided by the depth at which the particle is absorbed in a detector consisting of multiple layers. The heavier antideuterons will stop deeper in the detector than the lighter protons and antiprotons. This three-pronged approach (X-rays, pions, depth) provides an extraordinarily robust signature for antideuterons. This is essential since the antideuterons are expected to be extraordinarily rare events, and must be distinguished from the more common antiprotons with a reliability of about one part in 10^7.

This basic primer on the GAPS concept provides the background for understanding the instrument design. The GAPS detector must have 1) a segmented time-of-flight (TOF) system which permits measurement of the incoming (anti)particle velocity (speed and direction) 2) a degrader – a piece of material which can slow down the (anti)particle 3) a target to capture the (anti)particle moving with near-zero speed and 4) a segmented X-ray detector which measures the deexcitation atomic X-ray energies and tracks the pions in the nuclear annihilation.

A. Proof-of-Principle Experiment

The pion tracking and depth-sensing techniques are well-understood from nuclear and particle physics experiments. Thus our initial tests of the GAPS concept, undertaken with NASA funding, concentrated on the completely novel aspect of the project: detection of the deexcitation atomic X-rays to identify antiparticles. There is an enormous literature on exotic atom physics, as a tool for fundamental atomic physics investigations, and for particle physics, because exotic atom spectroscopy is a method to probe the strong-nuclear force. But the exotic atom approach had not been exploited as a means of particle identification.

We performed two experiments at the KEK particle accelerator in Tsukuba, Japan in the summer of 2004 and 2005 [3]. This was the only facility in the world at which we could access a slow beam of antiprotons for proof-of-principle. The experiment is shown in fig. 2. Lead degraders slowed down the antiproton beam, and the antiprotons were captured into a variety of gaseous, liquid and solid targets including metals such aluminum, liquids such as carbon tetrachloride and gases such as carbon hexafluoride. The cylindrical target was surrounded by NaI(Tl) scintillator crystals that detected the atomic X-rays. The NaI(Tl), along with scintillating fiber arrays were used to detect the pions from the nuclear annihilation. . For each target the yield of atomic X-rays was directly measured per captured antiproton, and compared with theoretical models. Valuable information was also obtained on various sources of internal background in beam-target interactions. These data can then be used to estimate overall experiment sensitivity.

Fig. 2. GAPS KEK prototype consisted of 128 crystals of NaI(Tl) (25mm diameter, 5mm thick) in 16 boxes, hexagonally arrayed around a target. Accelerator antiprotons were stopped in various target materials and atomic X-rays and pions from subsequent nuclear annihilation were detected in the NaI crystals.

B. Balloon Experiment Design

GAPS is amenable to both satellite- and 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) shown in fig. 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 (~20-100 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 ~ 2 m^2. Si(Li) trackers have not been used in particle astrophysics, although Si trackers are use in particle physics, and in the currently flying PAMELA experiment. bGAPS will use 3 layers of Si(Li) detectors.

The Si(Li) must 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 (fig. 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.

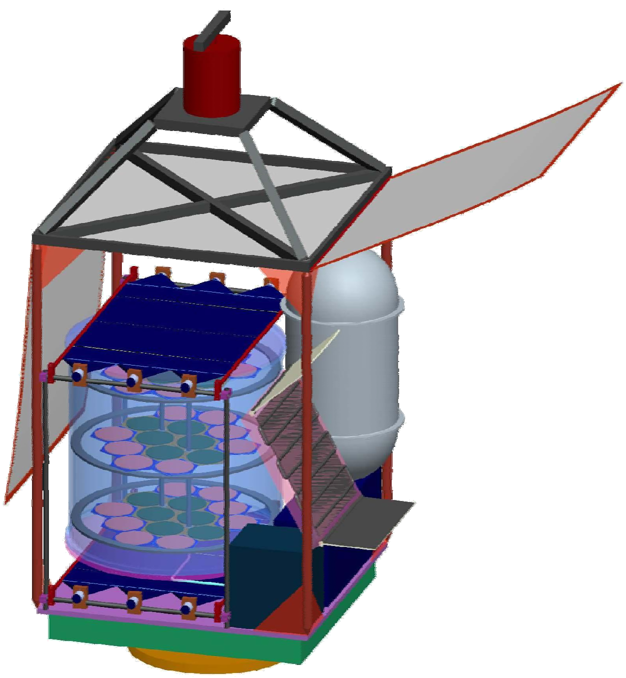

Fig. 3. Prototype GAPS experiment (pGAPS).

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 is to 1) confirm proper operation of the Si(Li) detectors at float altitude 2) measure X-ray and particle backgrounds of relevance to determining the overall instrument sensitivity 3) confirm the thermal model for predicting Si(Li) operating temperature and 4) verify the concept for cooling the Si(Li) detectors. Goal 1 is particularly important since the Si(Li) detectors will be operated at float altitude without a pressure vessel. This saves mass, and that is particularly important in a large area experiment like GAPS. 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 [4], 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.

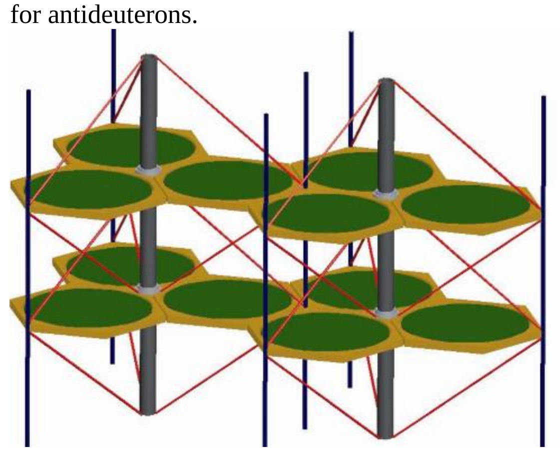

Fig. 4. Illustration of four base units, two cooling tubes, six vertical supports and multiple cross supports.

The pGAPS experiment is anticipated to take place in late 2009 from Hokkaido, Japan.

III. SCIENCE OF bGAPS EXPERIMENT

A. *Searches for Dark Matter*

The primary purpose of bGAPS is to detect antideuterons – the debris of WIMP annihilation in our galaxy. 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. It is worth mentioning here that accelerator-based experiments such as the LHC can do missing mass experiments to infer new physics beyond the standard model, only direct or indirect techniques will "discover" cosmological DM.

Fig. 5 illustrates the key features of a DM search with bGAPS. Shown are model predictions for the antideuteron flux expected from three different candidates for the DM [5]. The LSP is associated with SUSY models, and the LKP and the LZP are associated with UED models. These three particles together constitute the most popular candidates for DM. bGAPS 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 [6]. Secondary and tertiary antideuterons are those produced by conventional interactions of high energy protons and Helium nuclei with Hydrogen and Helium atoms in the interstellar medium. These conventional antideuterons are greatly suppressed with respect to the "primary" antideuterons – those associated with WIMP annihilations. And finally fig. 5 shows the sensitivity to antideuterons for a bGAPS experiment ranging in duration from 60 days (3 long-duration balloon flights from Antarctica) to 300 days (an ultra-long duration balloon capability that might be realized by the projected 2012 launch date of bGAPS).

Three features are worth noting. Firstly, bGAPS represents a 3 orders of magnitude improvement over the current state of the art, as represented by the BESS-Polar experiment, currently flying from Antarctica. The current generation of balloon-borne experiments cannot reach the types of sensitivities necessary to mount a serious search for DM. Secondly, bGAPS has the necessary sensitivity to discover DM via its antideuteron signature. And thirdly, for the sensitivity of a bGAPS experiment, the detection of even a single antideuteron is unambiguous evidence for the existence of DM. The secondary and tertiary background of antideuterons lies more than one and a half orders of magnitude below the bGAPS sensitivity, so only primary antideuterons – associated with DM – can be detected.

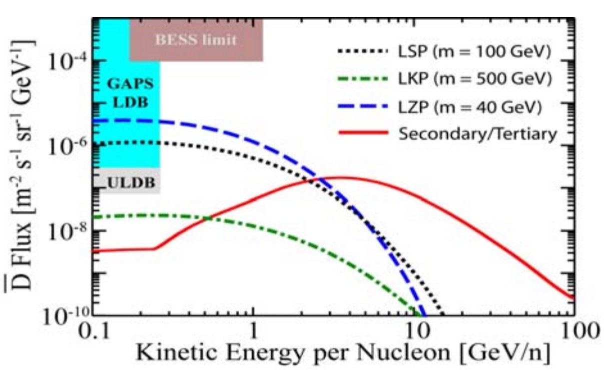

Fig. 5. LSP, LKP and LZP search with bGAPS along with the Secondary/Tertiary background and the reach of bGAPS and BESS.

bGAPS has the additional advantage in that it is a unique experiment; it covers an exceptionally broad area of discovery space for DM, where other methods may yield no signal at all. Whether a given signature (e.g., gamma-ray, neutrinos, antideuterons, direct scatter off nuclei) of DM is present, and the strength (count rate) of that signal, depends on fundamental physics parameters associated with a given model for the DM. The underground DM experiments cover essentially an overlapping region of this physics model parameter space. bGAPS, on the other hand, covers part of the space where underground techniques are sensitive, and part of the space where underground techniques are insensitive. The overlap region provides tighter constraints on the nature of DM, and the complementary regions represent unique discovery space for bGAPS.

This is illustrated in fig. 6 with a plot of the sensitivity of CDMS-II, a premier underground DM experiment, versus the sensitivity of bGAPS. The former is characterized by a scattering cross-section (associated with the count rate of detected WIMPS) and the latter by the antideuteron flux, reflecting the rate of WIMP annihilation in the galaxy. The red dots represent predicted detection rates for both CDMS and bGAPS given a specific set of parameters which describe the WIMP. In this case, the parameters are associated with a specific SUSY model – the MSSM model. Each dot represents dozens or hundreds of models whose parameters produce the given count rates. SUSY or UED models involve many parameters, so there is a degeneracy in count rates predicted for various model parameters. What is most important to note is that there are 4 quadrants to the plot, delineated by the horizontal yellow line, and the 4 vertical lines. The region above the yellow line corresponds to SUSY models already ruled out by CDMS-II. The region to the right of the various vertical lines (each corresponding to a different bGAPS experiment with sensitivity increasing from the right to left vertical lines) is the region that would be excluded by bGAPS. The region marked "GAPS only" corresponds to the part of SUSY parameter space where DM can be discovered, and only detected by bGAPS. The region marked both represents opportunity for mutual discovery by CDMS and bGAPS and so forth. This plot dramatically illustrates the important role space-based searches can play in the hunt for DM. There is a region of parameter space where the ~ thirty underground experiments will never discover DM. bGAPS alone can make the discovery in this quadrant. Thus the argument for a bGAPS experiment to cover this region is quite compelling.

B. Searches for Primordial, Evaporating Black Holes

bGAPS has been optimized to hunt for DM. However it is uniquely suited to another extraordinarily exciting science task – the hunt for primordial black holes (PBH). The prediction of PBHs follows from the existence of a hot phase in the early universe that has density fluctuations which can collapse to form PBHs. PBHs evaporate with the emission of gamma rays, antiprotons and antideuterons. It has been argued that the most sensitive search for PBHs can be performed with antideuterons [7]. bGAPS could improve the current best PBH limit by a factor of ~5-20 in a 300 day flight. Recently it has been suggested that antideuteron detection could even produce a lower limit to the reheating temperature at the end of inflation, and a lower limit to the mass of the gravitino. Thus bGAPS could be brought to bear on questions of early universe cosmology and quantum gravity. Of course there is a degeneracy in that antideuterons can, in principle, be detected from both evaporating PBH and WIMP annihilation. However this degeneracy can be broken with fundamental particle physics measurements that will be taken at the soon-to-be-operating LHC experiment [8].

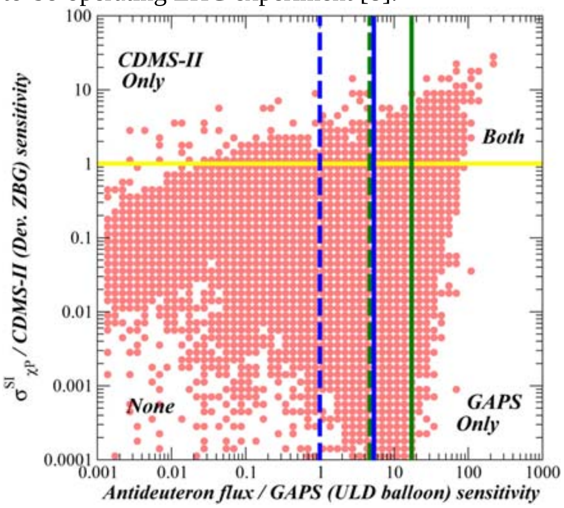

Fig. 6. Quadrant plot of the CDMS-II vs GAPS sensitivity.

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