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The GAPS Experiment: Hunting for Dark Matter with Antideuterons

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Abstract: The General Antiparticle Spectrometer (GAPS) experiment is an indirect dark matter search that aims to detect low-energy antideuterons resulting from dark matter annihilations in the galactic halo. This signature, which has negligible conventional astrophysical background, is predicted by many models of both supersymmetry and extra-dimensional theories. Until now, an optimized low-energy search experiment has been lacking. In this contribution, the scientific and experimental case for GAPS will be reviewed, and its complementarity with existing indirect and direct search experiments will be discussed. We will describe the design of GAPS, which consists of a time-of-flight system and layers of Si(Li) detectors in a tracking geometry designed specifically for low-energy antideuteron detection. The results of our successful prototype balloon flight (pGAPS), which flew from Japan in June 2012 and met 100% of its mission goals, as well as the path forward to a science flight of GAPS from Antarctica, will be presented.

Keywords: dark matter, GAPS, antideuterons.

1 Antideuteron Searches for Dark Matter

The search for the origin of dark matter, the mysterious matter known to dominate the universe, is one of the overarching quests of contemporary astrophysics. The existence of enough hidden, heavy, normal objects to account for this dark matter has been ruled out by astronomical surveys, and instead current experiments focus mainly on searching for entirely new particles that will make up this mass. The most popular type of such potential particle is a weakly interacting, massive particle, known as a WIMP.

Over a decade ago, it was proposed that antideuterons produced by WIMP-WIMP annihilations in the galactic halo provide a particularly low-background signature of dark matter [1]. In this process, WIMPs annihilate via some beyond the Standard Model process, producing particles that then hadronize to an antiproton and antineutron pair. In the coalescence model, the antiproton and antineutron then combine to form an antideuteron if their momentum difference is below some cutoff value, p_0. The resulting flux of WIMP-produced (primary) antideuterons is relatively flat in the $\sim$0.1-1.0 GeV/n energy range, while those produced by cosmic ray interactions with the interstellar medium (secondary) and subsequent energy loss (tertiary) have fluxes that sharply decrease with decreasing energy. This yields improved sensitivity compared to, in particular, antiproton searches, since the higher energy required to create an antideuteron and the steeply falling cosmic ray energy spectrum make low-energy antideuterons harder to produce than antiprotons. A detectable antideuteron flux is predicted by cold dark matter (CDM) candidates such as the neutralino, Kaluza-Klein particles, Dirac right-handed neutrinos [2], and gravitinos [3].

Despite antideuterons being a low-background signal for

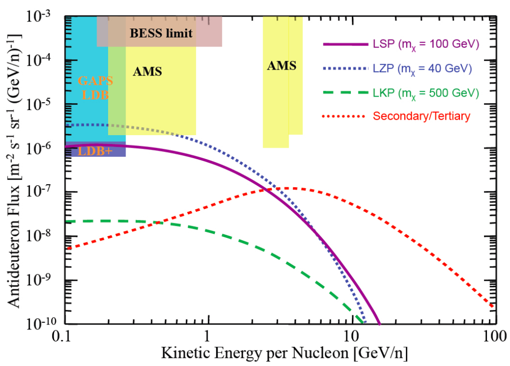

Figure 1: Antideuteron flux expected from LSP, LKP, and LZP models [2] and secondary/tertiary astrophysical background [4] [5], as well as the sensitivity of GAPS (long-duration and ultra-long duration balloon flights), BESS [6], and AMS (5 year) [7].

a variety of generic CDM candidates, there has so far been no dedicated low-energy antideuteron dark matter search experiment. The BESS balloon experiment upper limits are three orders of magnitude above the predicted dark matter flux levels [6]. In the coming years, the AMS experiment will also be sensitive to antideuterons [7]. However, this is a modest assault compared to the multitude of other rare-event dark matter searches, for example the dozens of operating or planned direct nuclear recoil experiments. The General Antiparticle Spectrometer (GAPS) is the first experiment optimized to search specifically for low-energy antideuteron byproducts of dark matter interactions. Figure 1 shows the flux expected from three benchmark dark matter candidates, the lightest supersymmetric particle (LSP), the lightest Kaluza-Klein particle (LKP), and a 5D-warped GUT Dirac neutrino (LZP) [2], as well as the expected secondary/tertiary background [4] [5]. Also shown is the sensitivity of a GAPS ~100 day and ~200 day Antarctic balloon mission (achievable with a series of long-duration balloon flights), of the BESS balloon flight, and of the AMS experiment with 5-years integration time. As illustrated in this plot, GAPS will improve the current BESS upper limit on antideuterons by ~3 orders of magnitude and provide ~1.5(3) times better sensitivity than AMS 5-year for the full LDB(LDB+) program, with the potential to actually discover DM as predicted by realistic models.

These model predictions are of course subject to several uncertainties. The dominant uncertainty for primary antideuterons is due to the propagation model, in particular the uncertainties in the halo and diffusion parameters [8]. There is some uncertainty due to the halo model itself, but since antideuteron production samples the full Galactic halo it is not very sensitive to the particulars of the halo density profile. Recent work has also emphasized uncertainties in the hadronization model used to predict the formation of the antideuteron from the antiproton-antineutron pair [5] [9]. An additional uncertainty is the so-called boost factor, f, due to "clumpiness" in the dark matter halo. The predictions presented here use a conservative value of $f = 1$, but recent theoretical consensus indicates that $f \sim 1-10$ [10]. The dominant uncertainty for the secondary and tertiary antideuterons is due to production cross sections, with propagation uncertainties less important because these background antideuterons are produced in the galactic disk, not halo. These uncertainties, along with the small predicted signal flux, highlight the need for multiple experiments with complementary sensitivities.

GAPS provides vital overlap with existing direct and indirect search experiments. This is essential, especially in regions where astrophysical backgrounds are poorly understood. Also, since direct detection probes WIMP scattering cross sections, and indirect detection probes annihilation cross sections, joint experiments can better constrain model parameters. For example, antideuteron searches provide sensitivity to neutralino masses both lower and higher than the optimal sensitivity range of direct detection experiments [8]; produce complementary coverage of the $b\bar{b}$ channel of neutralino decay, where Fermi observations of dwarf spheroidal galaxies are beginning to place lower mass limits of a few tens of GeV [11]; and probe both complementary and independent swaths of the large mSUGRA parameter space compared to LHC experiments.

2 GAPS Design

The GAPS experiment is designed to exploit particle velocity measurements, depth sensing, and X-ray and charged particle detection to uniquely identify antideuteron events. The basic design concept is as follows [12]. First, the velocity of an antiparticle that has been slowed by the atmosphere is measured by a plastic scintillator time-of-flight (TOF) system. The antiparticle then loses energy through interactions with layers of semiconducting, lithium-drifted silicon (Si(Li)) targets/tracking detectors. Eventually, the antiparticle stops in the target, forming an exotic atom in an excited state. This atom then de-excites, emitting X-rays with each transition. Finally, the nucleus annihilates, producing a shower of pions and baryons.

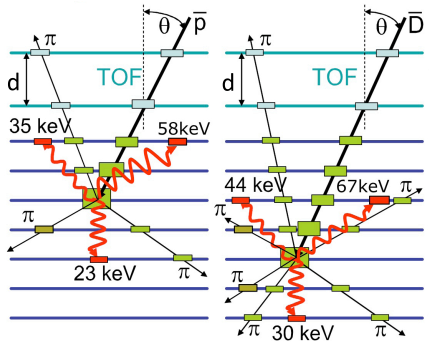

Figure 2: Typical antiproton and antideuteron interactions in the GAPS detector [12].

The precise energies of the emitted X-rays then depend solely on the mass and charge of the antiparticle that was incident on the Si target, and the number of shower particles emitted is roughly proportional to the number of nucleons in the antiparticle. The coincidence of X-rays with the proper energies and the emission of a shower of particles yields a signature of antideuteron production that is enormously good at rejecting background.

The interaction of antideuteron with the detector, as well as that of its most challenging background, antiprotons, is illustrated in Figure 2. The combination of TOF and incident angle give a velocity measurement. For the same velocity, an antideuteron will cross more layers of detector, emit X-rays of different energies, and produce twice as many shower particles. Preliminary studies focusing on depth sensing *alone* indicate that GAPS can reject at least 99% of protons/antiprotons while still achieving ~80% efficiency for antideuterons. Other major sources of background include temporally coherent X-rays, which are X-rays caused by elastic neutron scattering that are coincident with the antiparticle or X-rays produced by the showering pions, as well as temporally incoherent X-rays, which are caused by absorbed and Compton-scattered atmospheric and cosmic gamma rays, cosmic ray-produced neutrons, and gamma rays produced by cosmic rays interacting with support structures. Our studies indicate that a combination of depth sensing, shower particle multiplicity, dE/dx measurements, and atomic X-ray identification can yield antideuteron detection confidence levels of $> 99\%$.

The GAPS design, including the TOF and Si(Li) tracker systems, is shown in Figure 3. The current design calls for 10 planes of 4"-diameter, 2.5-mm-thick semiconducting Si(Li) detectors, forming a 2 m x 2 m x 2 m cube. Semiconducting Si(Li) detectors provide excellent time and energy resolution, both of which are necessary to distinguish between atomic X-ray transitions and background X-rays. At this thickness, they also have high escape fractions for X-rays down to ~20 keV, allowing the detectors to be both target for the incoming antideuteron and detector for the outgoing X-rays and particles. The channel size of four strips per detector provides sufficient spatial resolution to provide track and depth reconstruction, with a negligible probability that more than one X-ray or particle will simultaneously cross a single strip. As the final experiment will require ~2800 of these detectors, they are being produced in-house to reduce costs, using a simple fabrication procedure pioneered in the 1960s [13].

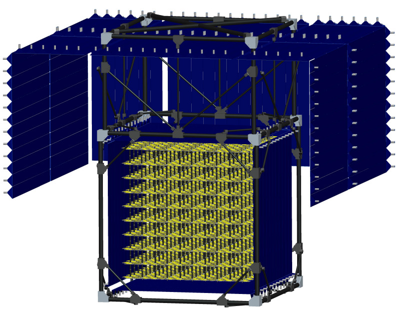

Figure 3: GAPS detector design, including TOF (blue) and Si(Li) tracker (yellow) systems.

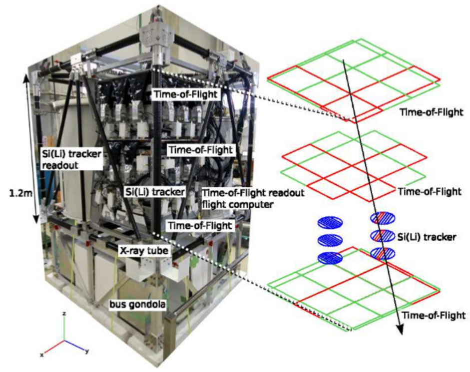

Figure 4: pGAPS payload (left) and a reconstructed cosmic-ray track from flight data passing through the three layers of TOF and three Si(Li) strips (right). [14]

The GAPS detection principle requires that the readout of the Si(Li) system provide high-resolution spectroscopy of low-energy X-rays and coarse-resolution spectroscopy of outgoing particles resulting from the nuclear decay. The X-ray mode requires energy resolution of $\sim$3 keV over the range 10-100 keV, while the particle mode requires $\sim$10% FWHM energy resolution over the range 1-50 MeV. This performance is delivered using a custom pre-amplifier and ASIC, to reduce power consumption.

The TOF system is essential to distinguish between high-mass and low-mass incident particles via their depth of stopping. It also provides a high-speed trigger and veto system. Plastic paddles of size 0.5 cm x 16.5 cm x 200 cm attached to high-speed PMTs will provide timing resolution of 500 ps. One layer of these paddles will completely surround the cube of Si(Li) detectors, as well as a second layer located 1 m from the top and covering partway down the sides.

To provide the required energy resolution, the Si(Li) detectors must be operated at $\sim$-35 C. A cooling system has been designed in which the structural support also acts as a single-pass heat exchanger, allowing the flow of Fluorinert coolant between detectors and a 3 m^2 radiator, oriented towards space, that maintains the coolant at -45 C. The power for GAPS will be provided by 13 m^2 of custom solar panels, which will also act as a shade for the detector system.

3 pGAPS

To test key detector technologies, a prototype GAPS (pGAPS) instrument was flown from Taiki Aerospace Research Field in Japan in June 2012 [14] [15] [16]. The three main goals of this flight were: (1) to verify stable, low-noise operation of Si(Li) detectors at ambient flight pressure, (2) to validate the cooling system and thermal model for the Si(Li) system, and (3) to measure the background levels at flight altitude to validate simulation codes for the final GAPS flight. Since Si(Li) detectors had never been used in a balloon flight before, the first goal would allow us to design GAPS without a pressure vessel system, whose necessity would allow less mass for the active detector system. Verification of the cooling system was essential to providing low-noise Si(Li) detector operation.

The pGAPS payload is shown in Figure 4. The science portion consisted of six 4"-diameter detectors, obtained from a commercial supplier, arranged in three layers. Surrounding this was the TOF system, with two layers of scintillator paddles above and one layer below. Each layer consisted of two crossed planes, with six paddles (each 0.3 cm x 50 cm x 15 cm) in the top and bottom layer and four paddles in the middle. A cooling system representative of the closed-loop, forced-convective fluid cooling system designed for the final GAPS mission was used to cool the Si(Li) detectors. Foam insulation on five sides protected the payload from direct and albedo radiation, with the portion of the sixth side that contained the radiators open to space. Two trigger modes were implemented, allowing to trigger events based on either the TOF system alone or the Si(Li) system. The lower section of the payload contained an oscillating heat pipe (OHP) [17] system attached to a dummy heat load to test an alternative, low-power cooling system approach; lithium batteries for power supply; and bus equipment for JAXA's balloon operations. A rotator located on top of the payload was designed to use information from a GPS compass, a gyro, and fish-eye camera to orient the radiators of the cooling systems away from direct sunlight.

pGAPS launched on June 3, 2012, staying aloft for $\sim$6 hours total, with over 3 hours at the float altitude of 31-33 km. A total of $\sim 8 \times 10^5$ TOF triggers of background events, $\sim 6 \times 10^5$ combined TOF and tracker triggers of background events, and $\sim 3 \times 10^6$ tracker triggers of X-ray calibration signals were collected. An example of a reconstructed cosmic-ray event is shown in Figure 4.

In three years operating the pGAPS Si(Li) detectors with no passivation coating, no degradation in the energy resolution has been observed. Figure 5 shows the resolution pre- and post-flight in the ground setup and pre-flight in the payload setup measured using an Am-241 X-ray source, with the low-energy hump in the payload configuration due to scattering from surrounding material. Pre- and post-flight, the resolution was measured using optimized ground electronics, which will be the basis for GAPS; the payload configuration used noisier flight electronics, which were adapted from another experiment. During the flight, the energy resolution was measured using an Ag-filter X-ray source. Detector gains were stable throughout the flight, and energy resolution was always consistent with the predictions for the given operating temperature as determined prior to flight. Thus the pGAPS results validate that Si(Li) detectors will meet our performance requirements without a passivation layer and at ambient pressure.

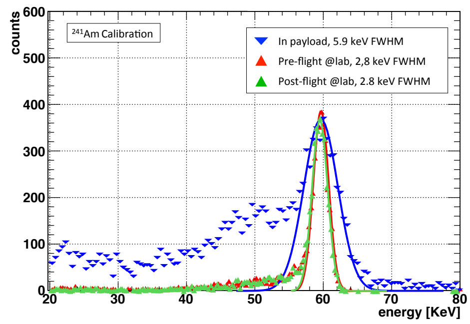

Figure 5: Am-241 59.5 keV X-ray line as measured by one Si(Li) channel pre-flight (red), in the payload configuration (blue), and post-flight (green).

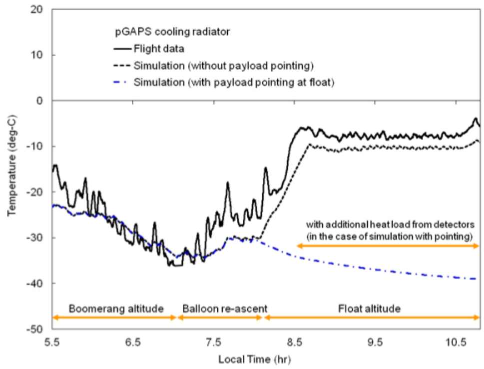

Figure 6: Temperature at pGAPS radiator as measured during flight (solid black), as predicted using the thermal model with radiator orientation rotating freely (dashed black), and as predicted with the radiator maintaining its pointing away from the sun (dashed blue) [14].

The thermal model of pGAPS was also confirmed using flight data. Due to an operatorational error, the rotator was not functioning at float altitude, and the side of the gondola containing the radiator spun freely between the sun and anti-sun orientation. However, all data from the aspect reconstruction system and the many temperature sensors throughout the payload were recovered. A flight-representative thermal model was built, including the altitude-dependent ambient air densities and temperatures, as well as the alternating solar gain and radiative cooling due to payload rotation. This model correctly predicts all temperatures on the payload, including those measured on the Si(Li) detector frames. The temperature at the radiator during the flight is compared with the simulation results in Figure 6. The same simulation predicts, for proper anti-sun radiator orientation, that the radiator temperature necessary to cool the Si(Li) detectors to their optimal operating point would be achieved.

4 Future Status

Using the knowledge gained from the successful pGAPS flight and three years of Si(Li) detector development, work is now progressing towards a full GAPS payload. The main milestones of this effort are: to either achieve similar high-yield, high-performance production of 4”-diameter Si(Li) detectors as has already been demonstrated with 2”-diameter detectors, or to fallback to an existing design that utilizes 2”-diameter detectors to yield the same sensitivity quoted above; to implement a scaled-up facility for batch processing of all flight detectors; to increase the TOF paddle length from 0.5 m to 2 m, verifying mechanical integrity, signal size, and timing performance; and to develop ASICs, based on existing prototypes, for both Si(Li) and TOF systems, as well as a custom pre-amplifier for the Si(Li) detectors. Building on the instrument experience gained so far, these goals are achievable, allowing for an initial GAPS flight in winter 2017/2018.

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