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The prototype GAPS (pGAPS) experiment

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ABSTRACT

The General Antiparticle Spectrometer (GAPS) experiment is a novel approach for the detection of cosmic ray antiparticles. A prototype GAPS (pGAPS) experiment was successfully flown on a high-altitude balloon in June of 2012. The goals of the pGAPS experiment were: to test the operation of lithium drifted silicon (Si(Li)) detectors at balloon altitudes, to validate the thermal model and cooling concept needed for engineering of a full-size GAPS instrument, and to characterize cosmic ray and X-ray backgrounds. The instrument was launched from the Japan Aerospace Exploration Agency's (JAXA) Taiki Aerospace Research Field in Hokkaido, Japan. The flight lasted a total of 6 h, with over 3 h at float altitude ($\sim$33 km). Over one million cosmic ray triggers were recorded and all flight goals were met or exceeded.

1. Introduction

One of the great unanswered questions in physics and astronomy concerns the properties and composition of dark matter. Multiple (and independent) lines of evidence strongly suggest that there exist large quantities of mass in our universe beyond normal, baryonic matter. Currently, dark matter is most successfully explained by postulating some as-yet undiscovered particle (or particles). Numerous theories produce candidate dark matter particles. Some theories postulate very light particles, such as axions, while others predict much heavier candidates, generally known as weakly interacting massive particles (WIMPs), such as the Lightest Supersymmetric Particle (LSP) and others.

WIMPs would have a non-zero scattering cross-section with ordinary matter (thus justifying direct search experiments) and also self-annihilate into standard model particles (indirect detection). These annihilation products would be detectable potentially as an excess in either charged cosmic rays or in photons (X-rays or gamma rays).

Since the WIMPs would have no charge, any annihilation products should be split equally between matter and antimatter. Antideuterons in particular are comparatively rare in the cosmic rays (believed to be entirely of secondary/tertiary origin). Therefore, a clear excess in antideuterons above the flux expected from secondary/tertiary production would be strongly suggestive of dark matter [1].

2. GAPS science goals

A very promising indirect signature of dark matter is cosmic ray antideuterons. No primary astrophysical sources of antideuterons are expected, and antideuteron production from cosmic ray spallation in the interstellar medium is expected to be at least five orders of magnitude less efficient than for production of antiprotons [1]. To date, no cosmic ray antideuterons have been detected, and the experimental upper limits on the antideuteron flux are well above the antideuteron flux that might be expected from either dark matter self-annihilation or from spallation (see Fig. 1). Experiments with much higher sensitivity are needed.

An essential feature of a possible antideuteron excess from dark matter self-annihilation is the enhanced flux at lower energies (0.1–1 GeV/n) above the expected background from secondary/tertiary production (see Fig. 1). In fact, the contribution to the flux due to dark matter could be several orders of magnitude higher than the spallation contribution. Thus an antideuteron detection in

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this low energy region could be an essentially background free detection of dark matter. Additionally, the theoretical parameter space probed by this type of search is very complementary to direct detection experiments [3].

3. The GAPS technique

It is challenging to discriminate between matter and antimatter particles at high energies. Matter and their antimatter equivalents generally behave the same in calorimeters, scintillators, and other particle detectors. In order to determine a particle's charge, a strong magnetic field is usually required to deflect the matter and antimatter particles in opposite directions, and these particles must be tracked with good spatial resolution. This magnetic spectrometer technique has been used in a number of past and present experiments. However, magnetic spectrometers have some disadvantages, chief among which are a large mass and limited geometric acceptance.

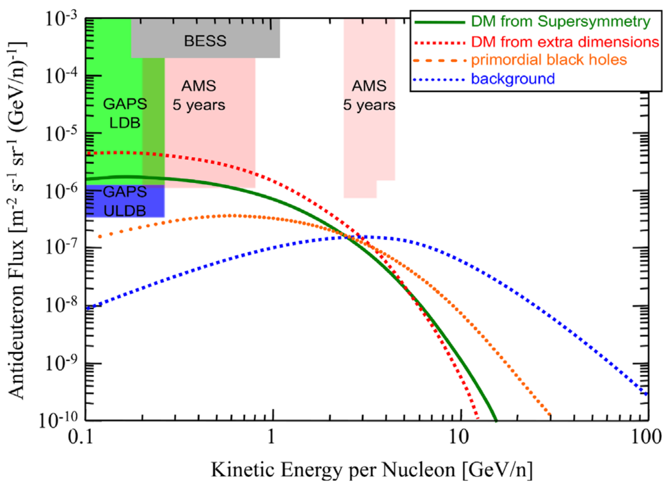

Fig. 1. Current antideuteron limits from BESS [2] shown with predicted antideuteron fluxes from different dark matter models [3] and primordial black holes [4], along with expected sensitivities for the operational AMS [5] and the future GAPS experiments. The expected antideuteron background from secondary production (spallation) is shown in the blue dashed line [6]. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

The GAPS technique does not rely on a magnetic field to discriminate particles from antiparticles. Instead, the (negatively charged) antiparticles (antiprotons, antideuterons, antihelium nuclei, etc.) are first slowed by a target mass until they can be captured in an atomic orbital of a target atom and form an exotic atom. The exotic atom very promptly deexcites, emitting X-rays of characteristic energy from the $N=8$, 7, and 6 orbital transitions, and finally annihilates on the nucleus, producing characteristic annihilation products, mostly pions and protons [7].

The energy of the atomic transition X-rays and the multiplicity of the pion and proton annihilation products are distinct for antiprotons and antideuterons, so the discrimination power of this kind of detector is very high. In order to make an unambiguous detection claim when searching for extremely rare particles such as the antideuteron, it is critically important to be able to suppress backgrounds efficiently, and the GAPS technique has very good rejection potential.

In 2004–2005 a series of GAPS prototype experiments were tested at the KEK accelerator facility in Japan. A number of different target materials were tested and the GAPS exotic atom technique was validated [8,9].

In a GAPS science instrument as envisioned here (bGAPS), the target and detector are entirely solid-state. Lithium drifted silicon (Si(Li)) wafers turn out to be a very good choice for the proposed technique. The material offers good X-ray energy resolution, as well as good sensitivity for charged particles, which is useful for tracking both the primary particle and the annihilation products. Also, a large array of Si(Li) detectors would act simultaneously as a degrader to slow down the primary particles and as a target material in which to produce exotic atoms. The only critical requirement for proper operation of the Si(Li) detectors is that they must be cooled to around −35 °C for good energy resolution.

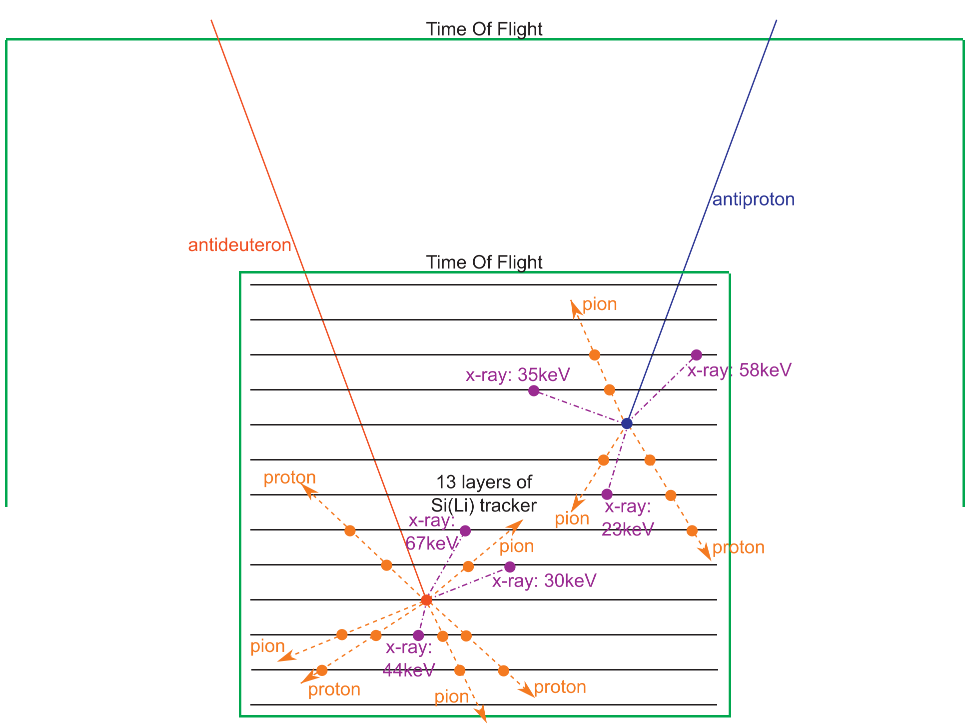

Fig. 2. bGAPS layout showing the anticipated event structure for an antiproton and antideuteron of the same velocity. The central Si(Li) structure is a 2 m cube.