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Current status and future plans for the general antiparticle spectrometer (GAPS)

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Abstract

We discuss current progress and future plans for the general antiparticle spectrometer experiment (GAPS). GAPS detects antideuterons through the X-rays and pions emitted during the deexcitation of exotic atoms formed when the antideuterons are slowed down and stopped in targets. GAPS provides an exceptionally sensitive means to detect cosmic-ray antideuterons. Cosmic-ray antideuterons can provide indirect evidence for the existence of dark matter in such form as neutralinos or Kaluza–Klein particles. We describe results of accelerator testing of GAPS prototypes, tentative design concepts for a flight GAPS detector, and near-term plans for flying a GAPS prototype on a balloon.

Keywords: Dark matter; Dark matter detectors; Cosmic-rays; Cosmic-ray detectors; Antiparticle; Antideuteron; Exotic atom; GAPS

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1. Introduction

The two most important goals of 21st century physics are to understand the nature and origin of dark energy and dark matter. WMAP, together with other experiments, has precisely determined the energy distribution in the universe (Spergel et al., 2003). Unfortunately, while we know that the matter makeup of the universe is dominated by dark matter, its nature still remains illusive. There are over 20 current or planned underground experiments that hope to directly detect dark matter from nuclear recoils; however, none cover a large portion of the available dark matter parameter space.

An alternate means of detecting dark matter takes advantage of the fact that dark matter particles also annihilate with themselves producing a variety of indirect signals in the cosmic radiation such as gamma-rays, positrons, neutrinos, antiprotons and antideuterons. Of these, antideuterons provide a particularly sensitive indirect signature of dark matter pair annihilation within supersymmetry (SUSY), as first pointed out by (Donato et al., 2000). While the antideuteron production is not as copious as other dark matter annihilation products such as antiprotons, the relative astrophysical background for antideuterons is significantly suppressed. Thus, especially at very low energies, antideuterons provide an essentially background-free technique for detecting dark matter.

Indirect antideuteron signatures of Cold Dark Matter (CDM) have also been explored within the context of other models such as minimal supergravity (Edsjo et al., 2004) as well as more complicated SUSY models (Profumo and

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Ullio, 2004; Masiero et al., 2005). Other studies have focused on CDM detection outside SUSY, namely universal extra-dimensions (UED) Kaluza–Klein and warped extra-dimensional dark matter models (Baer and Profumo, 2005). In some regions of these models, antideuterons are the only viable detection method, while in other regions antideuterons are competitive with direct detection or indirect detection of neutrinos from neutralino annihilation in the Sun.

In general, antideuteron searches are complementary to direct and other indirect detection methods in that they probe different portions of the allowed parameter space for a given model. In this way, multiple detection methods should be pursued to limit the available parameter space of the various models (excluding some altogether), or perhaps even confirm a reported discovery and thereby narrowing the underlying physics. Alternatively, an antideuteron detection could also signal evaporation of primordial black holes (Barrau et al., 2003). A first upper limit on the antideuteron flux at the top of the atmosphere of 1.9×10^{-4} $(\mathrm{m}^2\,\mathrm{s\,sr\,GeV/nucleon})^{-1}$, at the 95% confidence level, between 0.17 and 1.15 GeV/nucleon was recently set by the BESS experiment (Fuke et al., 2005). This is still nearly two orders of magnitude above the theoretical predictions.

The general antiparticle spectrometer (GAPS) is a novel concept for detection of antimatter. It is particularly well suited for low-energy antideuteron searches (where background production is most severely suppressed) and as a balloon experiment will probe more than three orders of magnitude deeper in sensitivity than BESS. The operating principles, designs and sensitivity calculations for potential balloon and satellite-based GAPS experiments have been previously reported (Mori et al., 2002; Hailey et al., 2004). Interim progress has also been reported on the performance of a GAPS prototype exposed to an antiproton beam, as well as various beams representative of cosmic backgrounds, at the KEK accelerator facility in Japan (Hailey et al., 2006).

In this paper, we describe the GAPS concept, the GAPS prototype experiment and analysis and plans for continued experimental work. We note that our preliminary analysis suggests that the GAPS concept is at least as promising as our previous simulations suggested, and thus recent theoretical analyses based on (Mori et al., 2002) remain unaltered by the current experimental landscape.

2. Operating concept of the general antiparticle spectrometer

The favorable signal to background of an antideuteron search comes at a price; the flux of primary antideuterons is very small. While this flux is clearly model dependent, for experiment search times of months to years the proper order of magnitude for the geometrical acceptance of an experiment is $\gtrsim 1$–$2\,\mathrm{m}^2\,\mathrm{sr}$. This is to be compared with current premier magnetic spectrometer experiments such as BESS-Polar, AMS/ISS, and PAMELA, which have smaller geometrical acceptances by approximately a factor of 10 (Galaktionov, 2002). In addition, it is not feasible to scale up the magnetic spectrometers for next generation searches for CDM. For balloon and space-based experiments, BESS and AMS likely represent the ultimate performance achievable given the respective payload mass limits.

GAPS was developed as a next generation antimatter detector. In (Mori et al., 2002) there is a detailed discussion of the atomic physics of GAPS, its design optimization and sensitivity calculations for various experiments. The interested reader is referred to this paper for a more extensive discussion. Below we describe the basic operating principles to elucidate the issues which must be addressed in prototype development.

An antiparticle passes through a time of flight (TOF) system (which measures energy after mass identification) and is slowed down by $\mathrm{d}E/\mathrm{d}x$ losses in a degrader block. The thickness of the degrader is tuned to select the sensitive energy range of the instrument. The antiparticle is stopped in a target, forming an excited, exotic atom with probability of order unity. The exotic atom deexcites through both autoionizing transitions and radiation producing transitions. Through proper selection of target materials and geometry, the absorption of the antiparticle can be tailored to produce three or more well-defined X-rays in the cascade to the ground state (we refer to these as 'ladder X-rays'). The target is selected so that the ladder X-rays with energies in the 20–200 keV range can escape with low losses and can be efficiently detected in common X-ray detectors. After the emission of the ladder X-rays the antiparticle annihilates in the nucleus producing a shower (star) of pions. The X-ray/pion emission takes place within nanoseconds. The fast timing coincidence between the characteristic ladder X-rays of precisely known energy (dependent only on antiparticle mass and charge) and the energy deposition induced by the pion star is an extremely clean antiparticle signature. The GAPS concept is only practical at extremely low energies ($\lesssim 0.3$ GeV/nucleon), where particles can be ranged out with low mass degraders (essential for balloon or satellite missions where low mass is paramount).

3. Experimental setup of 2004 and 2005 prototype experiments at the KEK accelerator

The GAPS prototype was tested at the KEK accelerator facility in Tsukuba, Japan, in two separate experiments done in 2004 and 2005 (Hailey et al., 2006). The experiments were performed using the Pi2 secondary beamline of the 12 GeV proton synchrotron. The Pi2 beamline is unseparated such that copious quantities of kaons, pions and electrons are transported to the experimental area along with antiprotons. The antiproton flux in the Pi2 beamline increases steeply with increasing momentum up to ~2 GeV/c. A momentum of 1 GeV/c was chosen to balance this increasing flux with annihilation and scattering losses in a degrader whose thickness must be tuned to stop the antiprotons in the GAPS target. The beam structure is

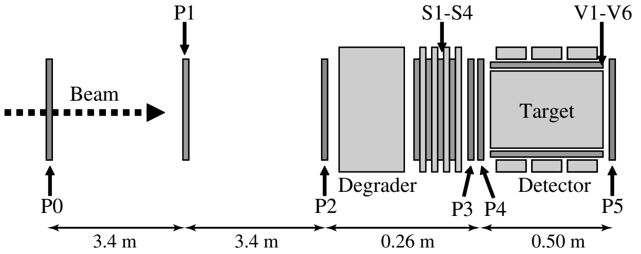

Fig. 1. KEK experimental setup. The detectors labeled from above were only included in the 2005 experiment. While this illustration is not drawn to scale, the distances between selected detectors is provided below for reference.

relatively flat with a 4 s spill repetition and a 1.5 s spill length. At 1 GeV/c, the rate of the initial antiproton entering the Pi2 beamline area is approximately 25 per spill, but most of the antiprotons either undergo direct in-flight annihilation within the degrader or are scattered directly into the GAPS detector such that only 0.2% of these actually stop in the GAPS target. This is to be compared with the pion rate of $\sim 1.5 \times 10^5$ per spill.

The experimental setup is illustrated in Fig. 1. The detectors labeled from above were added for the KEK 2005 run to provide additional information to more accurately normalize event types and rates. Since all particles initially have the same momentum, they can be identified by time of flight (TOF) due to their difference in mass using P0 and P2 plastic scintillator counters separated by 6.8 m. The P3 and P4 counters provide redundant timing and energy deposit information to tag the antiprotons that have survived passage through the degrader and enter the target. The P5 counter is used to veto antiprotons that did not stop in the target. The S1–S4 plastic scintillators interspersed with lead form a shower counter confirms the passage of a valid antiproton through its dE/dx loss signature.

The GAPS detector consists of sets of 2×4 NaI crystals ($25\ \mathrm{mm} \times 25\ \mathrm{mm} \times 5\ \mathrm{mm}$ thick) housed in 16 panels arranged in a hexagonal array. Each of the 128 crystals is coupled to a Hamamatsu RM1924a photomultiplier tube (PMT). These detectors surround a cylindrical target (12 cm diameter, 48 cm length) providing 31% solid angle coverage. The system achieves sufficient energy resolution to resolve the X-ray transitions of interest and 750 ns time resolution for coincidence rejection of background. The level of detector segmentation was chosen to balance cost with the desire to limit the occurrence of multiple X-rays or annihilation products entering the same crystal. A custom 128-channel data acquisition system was constructed to directly handle signals from the NaI detector phototubes (Ziock et al., 2006). In front of the NaI crystals, six charged particle veto counters (V1–V6) consisting of thin scintillating fiber bundles were added surrounding the target cell completely. These counters identify beam particles that scatter directly into the crystals.

4. Experimental results of accelerator experiments

A variety of solid (S, CBr_4, Al, C aerogel), liquid (CCl_4) and gas (C_2F_6 and N_2) targets were used in the 2004 and 2005 runs, with the intention of evaluating candidate targets for real space experiments. A major result of the two KEK runs was to demonstrate successful detection of multi-X-ray events from solid and liquid targets. This is a substantial improvement over the GAPS baseline design that relied on high pressure gaseous targets. Solid and liquid targets substantially ease handling and design requirements for space-based systems and reduce dead volume in the instrument.

As an example of the KEK results, Fig. 2a shows a carbon tetrabromide integrated X-ray spectrum for a dataset that is expected to have several thousand antiprotons stops. This spectrum was produced solely using selection criteria intrinsic to GAPS. In this case the cut required more than two ladder X-ray transitions and more than four total energy deposits. The spectrum of Fig. 2a clearly shows the bromine X-rays (whose capture probability is large compared to the carbon). Again correcting for accidentals, the X-ray ladder transition rates are consistent with high X-ray yields – comparable to those in the corresponding kaonic system. More detailed analysis is underway. There are several unidentified lines above $\sim$170 keV in bromine and other solid target spectra. Preliminary analysis suggests these are the nuclear excitation lines associated with the daughter nuclei produced in antiproton annihilation of the nucleus, as first observed by Barnes (Barnes et al., 1972), which may serve to augment the atomic X-ray ladder transitions.

Fig. 2b shows the signature of a carbon tetrabromide antiproton annihilation. X-rays are cleanly identified in four panels but there are no associated nuclear annihilation pions. The mean number of pions per annihilation is approximately five; however, the solid angle coverage of our prototype GAPS is rather modest at $\sim$31%. Further, neutral pions will decay immediately to gamma-rays with very small probability of energy deposit in our thin crystals. Thus the existence of such events with no detected charged pions is not unexpected. Fig. 2b also shows how we are able to confirm, independently of the GAPS event signature, that the event was induced by an antiproton. The boxes below the segmented crystal display give data on the upstream and downstream diagnostics. In particular, displays P1–P4 for the plastic scintillators indicate the timing deviation at each piece of plastic detector compared to that expected for an antiproton. In each case the timing deviation is within the timing resolution of the system ($\sim$1 ns). The counters S1–S4 show the monotonic increase in deposited energy. Here the magnitude in each counter is consistent with that expected for slowing down of an antiproton of proper incident momentum. This is in contrast to beam pions which would have -4 (-8) ns TOF in P1 (P2) and a constant $\sim$2 MeV energy deposit in each counter. Finally,

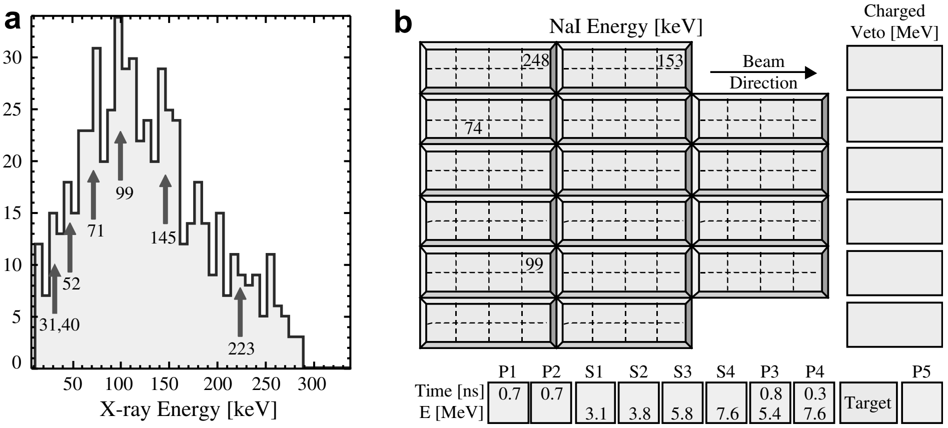

Fig. 2. (a) The carbon tetrabromide (CBr_4) integrated X-ray spectrum for events with $\geqslant 2$ ladder X-ray transitions and $\geqslant 4$ total energy deposits. (b) Event display for a four ladder X-ray event where the cylindrical detector and fiber veto detectors are shown ‘unwrapped’ from their geometry surrounding the target. The timing and energy deposit information in the P1–P5 and S1–S4 beam counters is also shown.

there is no signal in the downstream plastic detector P5 (indicating the tracked particle stopped in the target) and no signal in the scintillating fiber veto inside GAPS which would indicate an antiproton which elastically scattered out of the target cell. Elastically scattered antiprotons can be identified by the signatures they produce on capture and annihilation in the NaI itself.

5. Experimental implications

The most important result of the 2004 and 2005 KEK runs was to verify the basic GAPS concept. Simultaneous atomic ladder X-ray transitions and pion stars have been used, for the first time, to specifically identify antiparticles. GAPS provided near unity efficiency in identifying antiproton stops. These results were confirmed with a completely independent array of detectors which identify particles, by type, which stop in GAPS.

Two results of great importance to future design work were obtained. First, solid (and liquid) targets have been successfully utilized. This enormously simplifies the design challenges of GAPS. With no need for high pressure gas, as in the original concept, GAPS is easier to operate and it is lighter and more efficient because of the removal of the dead mass of the gas handling system. GAPS efficiency also increases because solid and liquid targets provide more design options. Gas targets must be both transparent to their ladder X-rays and immune to Stark mixing at high gas pressure. These were restrictive conditions given the limited number of gas candidates. Solid and liquid targets permit more choices where there are both more ladder X-rays in the detector bandpass and X-rays of higher mean energy. This translates directly into higher sensitivity, since loss of X-rays and particularly the lowest energy X-ray (the hardest to get out of the target and into the detector) dominates the sensitivity of GAPS. And second, the preliminary estimate of effective X-ray yield gives numbers consistent with the $\gtrsim 30\%$ used in the original GAPS sensitivity calculations.

Our conclusion from the experiments is that the GAPS concept is sound and that the sensitivity numbers of (Mori et al., 2002) are basically correct. Thus the theoretical implications of a GAPS experiment, discussed in numerous papers, will not be meaningfully altered when exact effective X-ray yields are produced from our detailed analysis. Two other results are of potential importance, although more work will be required to understand their implications. First, the pion stars provide substantial additional antiparticle identification capability, ignored in the original GAPS work. Second, the nuclear deexcitation lines, correlated with the atomic ladder X-rays, are potentially a source of added confirmation that an antiparticle stop has taken place.

6. Future directions for GAPS

The experimental program at KEK in Japan has been sufficiently successful to move on to a flight test of GAPS. We are currently evaluating several advanced flight detector concepts. Our main focus is on lithium drifted silicon wafers, Si(Li), which would be formed into p-i-n detectors with coarse ($\sim$2–4 cm) strips on one side and a thickness of $\sim$5 mm. They provide good energy (<2 keV) and timing ($\sim$200 ns) resolution. The complexity is fairly low because of the one-sided geometry and coarse pixelation, so they are relatively easy to produce. The challenge is the large number of wafers ($\sim$thousands) which are required to probe deep into the available parameter space of many dark matter models. Another important feature of these detectors is that they can be passively cooled on a balloon experiment so that no dewar or active cooling is required.

As currently envisioned, the balloon GAPS experiment will consist of 10 layers or $3 \times 3\ \mathrm{m}^2$ arrays of Si(Li) detectors, with a layer of target material sandwiched inbetween each detector layer. Each detector and target layer will be separated by 15 cm. Two layers of thin plastic scintillators separated by $\sim$1 m covering the top of the detector record incoming direction and time of flight (TOF) of incoming

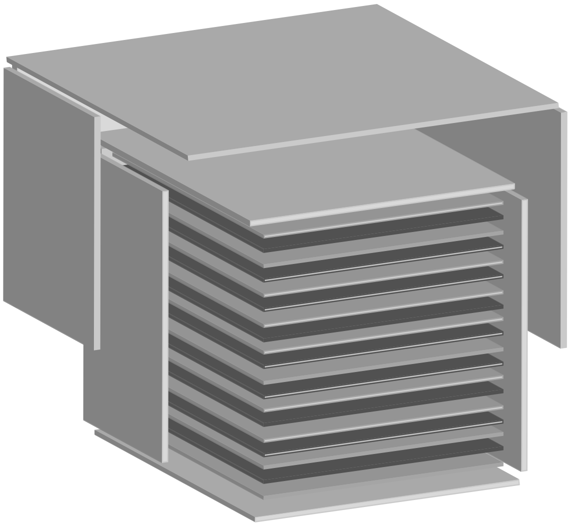

Fig. 3. Gaps Si detector design. Front and side portions of the plastic TOF counters, which surround the detector, are cut away to reveal alternating layers of Si(Li) detector and target material.

particles. The bottom half of the detector will be surrounded by only a single layer of plastic scintillator. Fig. 3 shows a cartoon of this concept.

In addition to providing sub-nanosecond TOF trigger for incident antiparticles, the plastic scintillators provide sub-nanosecond timing for all charged particles that are both incoming (e.g., extra background charged particles) and outgoing (e.g., charged pions from the nuclear annihilation) for optimal signature recognition and background rejection. As a TOF tagged incoming particle slows while passing layers of target and detector, the dE/dx energy losses recorded by the Si(Li) detectors will provide relatively good mass identification. This is important because the dominant background process for antideuterons is thought to be antiprotons with coincident accidental X-ray background events. However, an antiproton will slow quicker and stop much sooner than an antideuteron with the same incoming velocity. From preliminary simulations, the dE/dx recorded in the Si(Li) and the localization of the event stopping alone provide a factor of 100 to more than a 1000 in mass (i.e., antiproton vs. antideuteron) discrimination. This mass discrimination, together with the good timing and X-ray energy resolution of the Si(Li) detectors, provides the necessary background suppression to achieve the original GAPS sensitivity goals.

A balloon flight with a prototype instrument is planned to be carried out in 2008 in order to verify the new design and to characterize background processes. The most likely launch site for this first prototype flight is Sanriku, Japan. This first flight will lead to a GAPS instrument that can detect antideuterons with sufficient sensitivity to probe well into the parameter spaces of a variety of DM models. GAPS will be flown on a series of three long duration balloon (LDB) flights from Antarctica beginning in 2010. Each of these LDB flights is expected to last three weeks, and together they will achieve the sensitivity of $1.5 \times 10^{-7}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{GeV}^{-1}$. An ultra long duration balloon (ULDB) flight, when it eventually becomes available, would allow GAPS to achieve a sensitivity of $3.0 \times 10^{-8}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{GeV}^{-1}$.

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