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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

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} $(\mathrm{m}^2\,\mathrm{s}\,\mathrm{sr}\,\mathrm{GeV/nucleon})^{-1}$, 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 $\gtrsim 1\text{–}2\,\mathrm{m}^2\,\mathrm{sr}$. 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 dE/dx 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