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Antideuteron sensitivity for the GAPS experiment

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ABSTRACT

The General Antiparticle Spectrometer (GAPS) is a novel approach for indirect dark matter searches that exploits cosmic antiparticles, especially antideuterons. The GAPS antideuteron measurement utilizes distinctive detection methods using atomic X-rays and charged particles from the decay of exotic atoms as well as the timing and stopping range of the incoming particle, which together provide excellent antideuteron identification. Prior to the future balloon experiment, an accelerator test and a prototype flight were successfully conducted in 2005 and 2012 respectively, in order to verify the GAPS detection concept. This paper describes how the sensitivity of GAPS to antideuterons was estimated using a Monte Carlo simulation along with the atomic cascade model and the Intra-Nuclear Cascade model. The sensitivity for the GAPS antideuteron search obtained using this method is 2.0×10^{-6} $[\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}(\mathrm{GeV}/n)^{-1}]$ for the proposed long duration balloon program (LDB, 35 days × 3 flights), indicating that GAPS has a strong potential to probe a wide variety of dark matter annihilation and decay models through antideuteron measurements. GAPS is proposed to fly from Antarctica in the austral summer of 2019–2020.

1. Introduction

1.1. Dark matter and WIMPs

The recent result by the Planck experiment [1] shows that 68% of our universe is composed of dark energy, 27% is dark matter and 5% is baryonic matter. The nature and origin of dark energy and dark matter, however, are still unknown. This is one of the great cosmological problems of the 21st century. The existence of dark matter was postulated by Fritz Zwicky in 1933 from the observation of the Coma galaxy cluster [2]. Recent observations, such as gravitational lensing in the Bullet Cluster (two colliding clusters of galaxies), also indicate the existence of dark matter [3]. Weakly Interacting Massive Particles (WIMPs) are among the theoretically best-motivated candidates in the variety of dark matter models. The lightest supersymmetric partner (LSP) in supersymmetric (SUSY) theories such as neutralinos [4,5] and right-handed sneutrinos [6,7] as well as Kaluza–Klein particles, such as right-handed sneutrinos (LZP) [8] in extra dimension theories are examples of popular WIMP candidates. Gravitinos, known as Super Weakly Interacting Massive Particles (SuperWIMPs), are also favored dark matter candidates in SUSY theories [9].

1.2. Antideuterons as dark matter search

Dark matter searches are usually categorized into three types: particle colliders, direct searches, and indirect searches. The direct and indirect searches will measure the relic WIMPs in our universe, while the particle collider will try to create WIMPs. The detection methods and the background models for each search are different, but also complementary, helping to illuminate the nature of dark matter.

Indirect dark matter searches measure dark matter co-annihilation and decay products, such as electrons, positrons, gamma-rays, antiprotons and antideuterons. The General Antiparticle Spectrometer (GAPS) is a novel approach for indirect dark matter searches that exploits cosmic antiprotons and antideuterons [10,11] .

Antideuteron production in dark matter co-annihilations was proposed by Donato et al. [4,5]. The antideuteron flux at the top of the atmosphere due to dark matter co-annihilation and decay (called primary flux) can be estimated based on dark matter density profiles in the galaxy, dark matter co-annihilation and decay channels,

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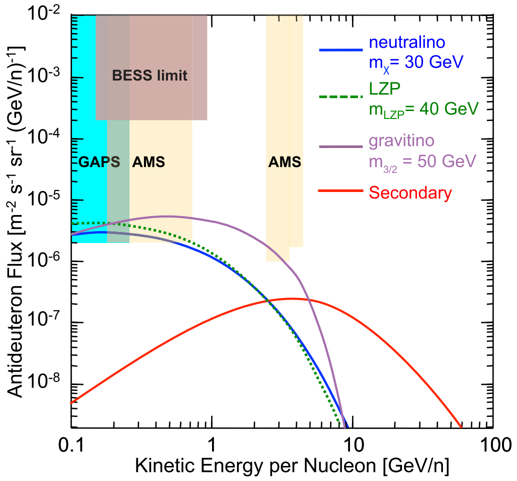

Fig. 1. Antideuteron flux at the top of the atmosphere. The solid blue and purple lines are neutralino and gravitino LSPs with $m_\chi \sim 30$ GeV [5] and $m_{3/2} \sim 50$ GeV [9] respectively, while the dashed green line is for LZP with $m_\chi \sim 40$ GeV [8]. The red solid line represents the secondary/tertiary flux due to the cosmic-ray interactions [12–14]. The expected GAPS antideuteron sensitivity (∼ 99% CL) as well as the AMS-02 sensitivity [15–18] and the current upper limit on the antideuteron flux obtained by BESS [19] are also shown (see Section 3.5). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

hadronization and coalescence models, propagation models and solar modulation models. The primary antideuteron fluxes for different dark matter models are shown in Fig 1. The solid blue and purple lines are neutralino and gravitino LSPs with $m_\chi \sim 30$ GeV [5] and $m_{3/2} \sim 50$ GeV [9] respectively, while the dashed green line is for LZP with $m_\chi \sim 40$ GeV [8]. The primary antideuteron flux has a relatively flat peak at low energy, $E \sim 0.2$ GeV/n. The antideuteron flux due to cosmic-ray interactions with the interstellar medium (called secondary/tertiary flux) is also shown as the solid red line in Fig. 1 [12–14]. Unlike primary antideuterons, collision kinematics suppress the formation of low-energy secondary antideuterons. Furthermore, the interaction rate is drastically decreased since the flux of the cosmic-ray protons follows roughly a power law, $F_p \sim E^{-2.7}$. Therefore, the primary antideuteron flux can be about two orders of magnitude larger than the secondary/tertiary antideuteron flux at low energy, which can provide clear dark matter signatures.

The Alpha Magnetic Spectrometer (AMS-02) on the International Space Station, launched in 2011, is the only currently-operating antideuteron search experiment. AMS-02 probes a higher energy region than GAPS, using a different detection technique with a completely different background [20]. GAPS complements AMS-02 on the antideuteron search, which is crucial for rare event searches, while uniquely seeking for lower energy and lower background antideuterons. GAPS also complements other existing and planned indirect searches as well as underground direct dark matter searches and collider experiments, while distinctively probing a wide variety of dark matter annihilation and decay models. The expected GAPS antideuteron sensitivity (∼ 99% CL) as well as the AMS-02 sensitivity [15–18] and the current upper limit on the antideuteron flux obtained by BESS [19] are also shown in Fig. 1. The details will be discussed in Section 3.5.

2. GAPS project

The GAPS experiment was proposed in 2002 [10], and the detection concept discussed below was validated in an accelerator beam test at KEK, Japan in 2005 [21] and the prototype flight (pGAPS) at JAXA/ISAS balloon facility in 2012 [15–17]. A GAPS science mission is proposed to fly from Antarctica in the austral summer of 2019–2020.

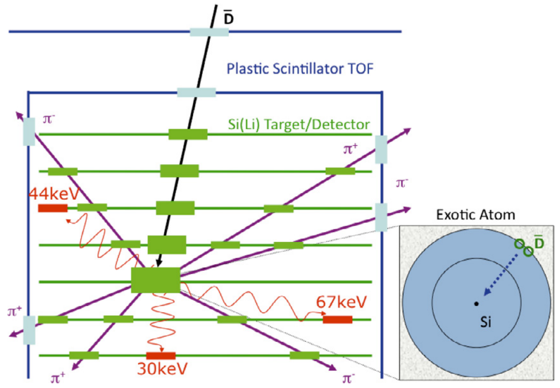

Fig. 2. GAPS detection method: an antiparticle slows down and stops in the Si(Li) target, forming an exotic atom. The atomic X-rays will be emitted as it de-excites followed by the pion (and proton) emission in the nuclear annihilation.

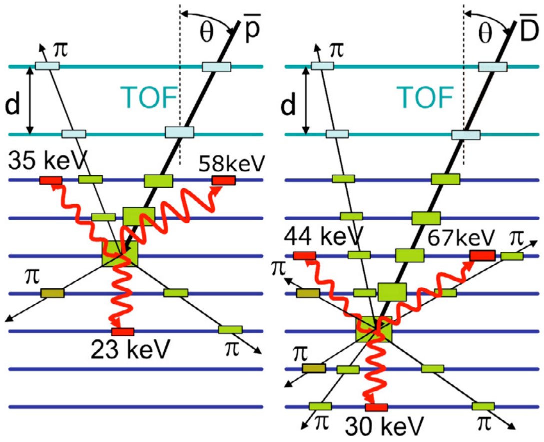

Fig. 3. GAPS antideuteron–antiproton identification technique: (1) unique atomic X-rays, (2) pion and proton multiplicity, (3) stopping range.

2.1. Detection concept

The GAPS detection method involves capturing antiparticles into a target material with subsequent formation of exotic atoms. A time-of-flight (TOF) system measures the velocity (energy) and direction of an incoming antiparticle. The antiparticle slows down by the dE/dX energy loss and stops in the target material, forming an exotic atom in its excited state. The exotic atom de-excites with the emission of Auger electrons as well as atomic X-rays [21]. With known atomic number of the target, the Bohr formula for the atomic X-ray energy uniquely determines the mass of the captured particle [10]. Ultimately, the antiparticle is captured by the nucleus in the atom, where it is annihilated with the emission of annihilation products, such as pions and protons. Since the mean number of pions and protons produced by the nuclear annihilation is approximately proportional to the number of antinucleons, the pion and proton multiplicities provide an additional discriminant to identify the incoming antideutron from other particles, such as antiprotons. This process is illustrated in Fig. 2.

Antiprotons are the main background in the GAPS antideuteron measurement since they can also form exotic atoms and simultaneously emit atomic X-rays and annihilation products. Antideuterons, however, are distinguishable from antiprotons with the atomic X-rays and annihilation products as discussed above. Furthermore, the stopping range of antideuterons, which is about twice as large as that of antiprotons with the same β, provides an excellent discrimination to distinguish antideuterons from antiprotons. Fig. 3 illustrates the GAPS antideuteron–antiproton identification technique with atomic