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A measurement of atomic X-ray yields in exotic atoms and implications for an antideuteron-based dark matter search

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ABSTRACT

The General AntiParticle Spectrometer (GAPS) is a novel approach for the indirect dark matter search that exploits cosmic antideuterons. GAPS utilizes a distinctive detection method using atomic X-rays and charged particles from the exotic atom as well as the timing, stopping range and dE/dX energy deposit of the incoming particle, which provides excellent antideuteron identification. In anticipation of a future balloon experiment, an accelerator test was conducted in 2004 and 2005 at KEK, Japan, in order to prove the concept and to precisely measure the X-ray yields of antiprotonic exotic atoms formed with different target materials [1]. The X-ray yields of the exotic atoms with Al and S targets were obtained as $\sim 75\%$, which are higher than were previously assumed in [2]. A simple, but comprehensive cascade model has been developed not only to evaluate the measurement results but also to predict the X-ray yields of the exotic atoms formed with any materials in the GAPS instrument. The cascade model is extendable to any kind of exotic atom (any negatively charged cascading particles with any target materials), and it was compared and validated with other experimental data and cascade models for muonic and antiprotonic exotic atoms. The X-ray yields of the antideuteronic exotic atoms are predicted with a simple cascade model and the sensitivity for the GAPS antideuteron search was estimated for the proposed long duration balloon program [3], which suggests that GAPS has a strong potential to detect antideuterons as a dark matter signature. A GAPS prototype flight (pGAPS) was launched successfully from the JAXA/ISAS balloon facility in Hokkaido, Japan in summer 2012 [4,5] and a proposed GAPS science flight is to fly from Antarctica in the austral summer of 2017–2018.

1. Introduction

1.1. Overview

The General AntiParticle Spectrometer (GAPS) is a novel approach for an indirect dark matter search that exploits cosmic antideuterons. Since the GAPS project utilizes atomic X-rays of exotic atoms to identify antideuterons (see Section 1.4), an accelerator test was conducted in 2004 and 2005 at KEK, Japan, in order to prove the concept and to precisely measure the X-ray yields of antiprotonic exotic atoms formed with different target materials [1]. This paper describes not only the detailed analysis for the X-ray yields for antiprotonic exotic atoms (Section 3), but also the development of a comprehensive cascade model for the exotic atom (Section 2). The cascade model was compared and validated with other experimental data and cascade models for muonic and antiprotonic exotic atoms. The results for the accelerator test were used to estimate the X-ray yields for antideuteronic exotic atoms in the GAPS flight experiment. The subsequent GAPS antideuteron sensitivity [3] indicates that the GAPS project has a strong potential to detect antideuterons as a dark matter signature.

1.2. Dark matter candidates

The recent result by the Planck experiment [6] shows that 68% of our universe is composed of dark energy, and 27% is dark matter ($\sim 5\%$ for baryonic matter). The nature and origin of these phenomena, however, are still unknown, and thus are the great cosmological problems of the 21st century. Unlike dark energy, dark matter is well-motivated by many theoretical models, and many experiments are currently being conducted to determine the origin of dark matter.

The existence of dark matter was postulated by Fritz Zwicky in 1933 from the observation of the rotational speed of galaxies. The recent observations of gravitational lensing in the Bullet Cluster

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(two colliding clusters of galaxies), also indicate the existence of dark matter [7].

Since dark matter has never been directly observed, it is considered to interact with the Standard Model particles only by the weak force and the gravitational force as seen in rotational curves and gravitational lensing. The small density fluctuations seen in the cosmic microwave background (CMB) [8] and the large scale structure of the present universe indicate that dark matter should be a non-relativistic and massive particle (called cold dark matter). Moreover, it should be stable on a cosmological time scale to be observed in the present universe. Weakly interacting massive particles (WIMPs) are the theoretically best-motivated candidates among the variety of dark matter candidates. Neutralinos, the lightest supersymmetric partner (LSP) in supersymmetric theories, and Kaluza–Klein particles (LKP) and right-handed neutrinos (LZP) in extra dimension theories are examples of popular WIMP candidates.

1.3. Antideuterons for dark matter search

There are dozens of experiments designed to search for particles associated with various manifestations of WIMP dark matter categorized into three types, particle collider, direct search, and indirect search. The direct and indirect searches will measure the relic WIMPs, while the particle collider will try to create WIMPs. The direct search measures the recoil energy of a target atom in the detector induced by the interaction with the WIMP, while the indirect search focuses on WIMP-WIMP annihilation products such as electrons, positrons, gamma rays, antiprotons and antideuterons. The detection methods and the background models for each search are different, but also complementary, helping to illuminate the nature of dark matter.

Antideuteron production in WIMP-WIMP annihilations was proposed by Donato et al., in 2000 [9,10]. The antideuteron flux due to WIMP-WIMP annihilation (called primary flux) can be estimated based on the dark matter density profile of the galaxy, the WIMP-WIMP annihilation channel, the hadronization and coalescence model, and the propagation model. The primary antideuteron flux at the top of the atmosphere due to the WIMP-WIMP annihilation is shown in Fig. 1 (solid purple line: LSP with $m_\chi \sim$ 100 GeV, dashed green line: LKP with $m_\chi \sim 500$ GeV, dashed blue line: LZP with $m_\chi \sim 40$ GeV) [11]. The relatively flat peak is located at $E \sim$ 0.2 GeV/n. The antideuteron flux due to the cosmic-ray interactions with the interstellar medium (secondary/tertiary flux, red dashed line) is also shown in Fig. 1 [12–14]. Unlike primary antideuterons, collision kinematics suppress the formation of low-energy secondary antideuterons. Moreover, the interaction rate is drastically decreased at high energy since the flux of the cosmic-ray protons follows the power law, $F_p \sim E^{-2.7}$. Therefore, the primary antideuteron flux is two orders of magnitude larger than the secondary/tertiary antideuteron flux at low energy, and we can clearly distinguish them.

The GAPS and AMS (5 year flight) sensitivities [3], and the current upper limit for the antideuteron flux obtained by the BESS experiment [15] are also shown in Fig. 1. The flight altitude for GAPS and BESS is $\sim$ 35–40 km ($\sim$ 4–5 g/cm^2 atmospheric depth), while AMS is on the International Space Station (ISS). As seen in the figure, the GAPS experiment is more than two order of magnitude more sensitive than the BESS upper limit and 1.5 times more sensitive than the AMS satellite mission. (The sensitivity for a GAPS 210 day flight program (LDB+) is also shown in the figure.) Thus, GAPS has a strong potential to detect antideuterons as the dark matter signature. In the following section, the details of the GAPS project are introduced including the detection concept and the instrumental design.

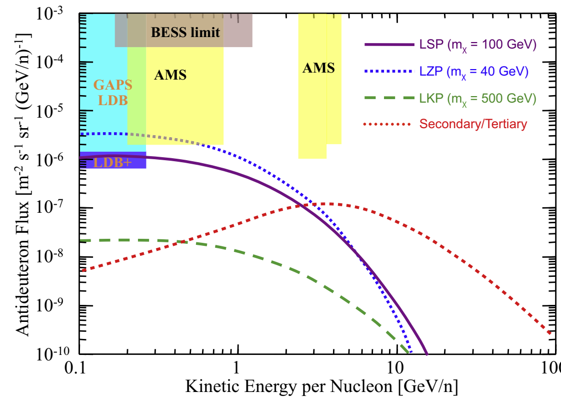

Fig. 1. Antideuteron flux at the top of the atmosphere, compared with the BESS upper limit [15], and GAPS and AMS sensitivity [3]. The flight altitude for GAPS and BESS is $\sim$ 35–40 km, while AMS is on ISS. The sensitivity for the AMS 5 year flight was estimated, based on [16]. The blue dashed line (LZP), black dotted line (LSP), and green dot-dashed line (LKP) represent the primary antideuteron fluxes due to the dark matter annihilations [11]. The red solid line represents the secondary/tertiary flux due to the cosmic-ray interactions [12–14]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1.4. GAPS project

1.4.1. Overview of the GAPS project

The GAPS project was first proposed in 2002 and was originally named the Gaseous AntiParticle Spectrometer [2,17]. The original GAPS was designed to use a gaseous target, but with further studies, including the KEK (high energy accelerator research organization) beam test in Japan described below, we concluded that a solid target was more efficient and effective for the flight experiment. GAPS is a balloon-borne experiment (flight altitude $\sim$ 35 km), and there are constraints on the size and mass of the payload. Therefore, the solid target can greatly simplify the setup of the GAPS flight module by removing the bulky gas handling system and allowing more complex designs, such as a multi-layer tracker geometry. The higher density of the solid target can also easily slow down and stop more incoming antiparticles, which provides a larger detectable energy range. A GAPS prototype flight (pGAPS) was launched successfully from the JAXA/ISAS balloon facility in Hokkaido, Japan in the summer of 2012 [4,5], and a proposed GAPS science flight is to fly from Antarctica in the austral summer of 2017–2018.

1.4.2. Detection concept

The GAPS detection method involves capturing antiparticles into a target material with the subsequent formation of an excited exotic atom. A time-of-flight (TOF) system measures the velocity (energy) and direction of an incoming antiparticle. It slows down by the dE/dX energy loss and stops in the target material, forming an excited exotic atom. The exotic atom de-excites in a complex process involving Auger ionization and electron refilling at high quantum number states, followed by the emission of X-rays at the lower quantum states (see Section 2). With known atomic number of the target, the Bohr formula for the X-ray energy uniquely determines the mass of the captured antiparticle [2]. Ultimately, the antiparticle is captured by the nucleus in the atom, where it is annihilated with the emission of pions and protons. The number of pions and protons produced by the nuclear annihilation is approximately proportional to the number of antinucleons, which provides an additional discriminant to identify the incoming antiparticle. The concept of the detection technique has