The GAPS experiment – a search for cosmic-ray antinuclei from dark matter

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Abstract. The General Antiparticle Spectrometer (GAPS) is a balloon-borne experiment that aims to study low-energy cosmic-ray antinuclei. A novel detection concept that utilizes the physics of exotic atoms allows GAPS to realize a large sensitive area, a low energy threshold, and a high identification capability for antinuclei. The primary goal is to search for antideuterons in the energy region <0.25 GeV/n, where they are predicted to be background-free probes for dark matter annihilation or decay in the Galactic halo. GAPS will also measure precise low-energy antiproton spectra, which provide crucial information about the source and propagation of cosmic rays. Three flights on long-duration balloons from Antarctica are planned; the first flight of GAPS is scheduled for late 2021. This paper presents the scientific motivation, detection concept, development status, and plans for GAPS.

1. Introduction
Low-energy (below ~1 GeV/n) cosmic-ray antideuterons are predicted to be a distinctive signal from WIMP (weakly interacting massive particle) dark matter [1-3]. The background antideuterons are produced in known physics process, that is an interaction between cosmic-rays (mainly proton and helium) and the interstellar medium. Due to kinematic requirements, these background antideuterons are heavily suppressed below several GeV/n, as displayed in Figure 1. On the other hand, signal antideuterons are produced by beyond-the-standard-model physics. They are produced by WIMP annihilation or decay in the Galactic rest frame, resulting in soft energy spectra, as seen in color lines in Figure 1. Therefore, antideuterons with energy below ~1 GeV/n are a nearly background-free channel for the indirect dark matter searches.

GAPS is a balloon-borne experiment that aims to study low-energy cosmic-ray antinuclei, focusing on antideuterons as the dark matter signal [4-8]. WIMP dark matter models with \( \mathcal{O}(10) \) GeV WIMP masses predict an antideuteron energy spectrum peaking below ~1 GeV/n, shown in Figure 1, and two orders of magnitude larger than the expected background in the energy region of interest for the GAPS. In certain models, \( \mathcal{O}(100) \) GeV ~ \( \mathcal{O}(1) \) TeV WIMPs also provide comparable antideuteron flux in the ~0.1 GeV/n region [1,2]. GAPS also aims to carry out a precise measurement of the cosmic antiproton spectrum in an unexplored low-energy region, which will provide helpful constraints on cosmic-ray propagation and source models. A complementary search for antihelium, for which hints of candidates have been presented by AMS-02 but in different energy region [9], will also be provided.
2. The GAPS concept

In the GAPS detection scheme, a novel technique which utilizes exotic-atom physics is adopted, allowing for a sensitive survey of cosmic-ray antinuclei in an unexplored low-energy region.

GAPS consists of a tracker and time-of-flight (TOF) system surrounding the tracker (Figure 2). The TOF system is made of ~200 scintillator paddles. The TOF system will generate a trigger for slow and light cosmic-rays for which it will measure the particle’s velocity $\beta$, incident angle, and $dE/dx$. The tracker consists of >1000 silicon detectors. It tracks the trajectory, measures $dE/dx$, and slows the incident particle. The particle captured by the silicon detector array forms an excited exotic atom with a silicon nucleus, if the incoming particle is an antinucleus. In the de-excitation of the exotic atom, characteristic X-rays are emitted by ladder de-excitation. Pions and protons are also emitted by the nuclear annihilation. These secondary products are tracked and measured by surrounding silicon detectors and scintillation counters. By combining these measurements, we identify cosmic-ray antinuclei. This detection concept allows for a more transparent and lighter apparatus allowing a larger acceptance for low-energy cosmic-ray antinuclei with respect to conventional magnetic spectrometer.

3. Design, developments and current status

3.1. Tracker

We adopt a lithium-drifted silicon (Si(Li)) detector for the tracker. It allows for obtaining a thick sensitive layer with relatively low cost. Our design goals are as follows: energy resolution <4 keV FWHM for 60 keV X-rays at ~40°C, thickness of 2.5 mm, sensitive layer >90% of the detector thickness, diameter of 10 cm, and 8 readout strips. Ensuring a uniform lithium drift into the large-diameter silicon wafers was a development issue. The high operating temperature (~40°C), far above the conventionally-used liquid-nitrogen temperature, was also a major issue, as it causes high leakage current (and hence noise). We successfully developed the mass-production method of the GAPS Si(Li) detector in collaboration with Shimadzu Corp., Japan [10,11]. It is the first scale mass production method of large-area Si(Li). Passivation and calibration procedures were also established and the mass production of >1000 detectors began in Jan. 2019. The current fabrication rate is ~70 detectors/month and the fabrication yield rate of detectors meeting the requirements is > 90%.
In the Si(Li) detector integration, four detectors are mounted on a custom-made aluminum plate (called a “module”). One layer consists of 36 modules, and ten layers are stacked vertically, forming the tracker. The front-end electronics with ASIC [12] are mounted on the module. The custom ASIC (SLIDER32; Silicon Lithium DEtector Readout) provides 32-channel readout and digitization. To achieve the wide dynamic range (10 keV – 100 MeV) for characteristic X-rays and charged particles, a low-noise charge-sensitive amplifier (CSA) featuring dynamic signal compression [13,14] has been developed. Prototype modules have been fabricated, and integration/performance tests are underway.

3.2. Tracker cooling
In our cooling system, heat generated by the silicon detectors is transported to the radiator mounted on the side of the payload by a newly-developed heat pipe system. It uses two-phase fluid as a coolant, whose latent heat allows for achieving a larger heat transport than sensible heat alone could provide. A uniform temperature distribution of the detectors can also be achieved. The driving forces of the coolant are gravity and pressure differences between heating and cooling sections; therefore, this is basically a passive system. The basic technologies have already been developed [15,16]. A prototype cooling system was constructed and tests in the thermal chamber are underway.

The radiator is required to be passively cooled below -55°C to achieve silicon detector temperatures below ~40°C. In such a low temperature, contribution from the convection of the rarefied atmosphere is non-negligible with respect to the lowered radiation heat transfer. To confirm the heat transfer coefficient of the atmosphere used in our thermal model and demonstrate the radiator cooling, we carried out balloon experiments. A scaled radiator with a scaled heat pipe onboard the prototype GAPS (pGAPS) [17] was launched by JAXA from Hokkaido, Japan in 2012. Piggy-back experiments of a scaled radiator were performed using NASA balloons launched from Fort Sumner, New Mexico in 2018/2019.

3.3. TOF system
The TOF system consists of plastic scintillator paddles of thickness 6.35 mm, width 16 cm, and lengths ranging from 1.2 m to 1.8 m. Six silicon photomultipliers (SiPMs) with 6 mm x 6 mm apertures are mounted on a custom preamplifier board and attached to each end of the paddles. This dual readout allows us to obtain position information for passing charged particles in each paddle. The signals from the preamplifier are sampled by the DRS4 ASIC (developed by Paul Scherrer Institut) and digitized on a custom DAQ (Data Acquisition) board.

The requirements for the TOF system are velocity resolution $\Delta \beta < 0.12/\beta$, charge reconstruction accuracy $<0.25e$ and angular resolution $<5^\circ$ for vertically-incident particles. The requirements for each scintillator paddle are: timing resolution of 500 ps for minimum ionizing particles (MIPs), photoelectron number $>50$ for a MIP, and position resolution $<10$ cm along the long axis of the paddle. The prototype preamplifier and DAQ board have been developed and performance tests are underway. Preliminary results show a timing resolution of 340 ps, which successfully meets the requirements. Detailed design and developments are given in Ref. [18].

3.4. Simulation study
The GAPS sensitivity for antideuterons was estimated as $2 \times 10^{-6}$ (m$^2$ s sr GeV/n)$^{-1}$ for 105 days flight by Ref. [6] in 2016. Based on recent progress on the detailed payload design, we are working on a more precise design implementation in the simulation code. Ongoing study of the algorithm for event reconstruction [19] will also contribute to updated projections of the sensitivity.

In the detector model using Geant4, not only the implementation of the full payload design, but also validation and implementation of physical processes including excited-exotic atom processes, are underway. Algorithms for trajectory reconstruction and likelihood analysis using physical parameters ($\beta$, $dE/dx$, stopping range, etc.) are under development. Neural network techniques are also being studied and will be implemented in the data analysis method.
4. Conclusions
GAPS is a balloon-borne experiment that aims to study low-energy cosmic-ray antinuclei. A novel detection concept utilizing the physics of exotic atoms will allow GAPS to realize a large sensitive area, low energy threshold, and high identification capability for antinuclei. The primary goal is to search for antideuterons in the energy region \(<0.25\ \text{GeV/n}\), where they are predicted to be essentially background-free probes for dark matter annihilation or decay in the Galactic halo.

Significant progress has been made on all aspects of the design. A large-area and thick silicon detectors with high operating temperature have been developed. The mass production of \(>1000\) detectors began in Jan. 2019. A custom readout ASIC with wide dynamic range has been developed and performance tests of the integrated detector module are underway. Development of the passive tracker cooling system, which uses a heat pipe with two-phase coolant, is now in its final stage and tests of the prototype system are ongoing. Preamplifiers with six SiPMs and DAQ boards for the TOF system have been developed, and performance tests of the TOF system were performed. Simulation studies of the implemented design and methods to improve sensitivity are underway.

Three flights on long-duration balloons from Antarctica are planned; the first flight of GAPS is scheduled for late 2021.

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