New indirect searches of Dark Matter with the GAPS experiment

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Summary. — The General AntiParticle Spectrometer (GAPS) is a long-duration ballon-borne experiment, designed to detect low-energy cosmic-ray antinuclei (below ~ 0.25 GeV/n) as potential indirect signal of Dark Matter. Unlike traditional detection methods – relying for example on magnetic spectrometers – GAPS employs a novel approach based on the formation, de-excitation, and decay of exotic atoms, enabling the identification of antinuclei without the use of a magnet. The mission will investigate the low-energy sector of the cosmic-ray spectrum that has remained largely unexplored, allowing for a critical test of theoretical models predicting the flux of low-energy antideuterons; in addition, GAPS is expected to achieve unprecedented sensitivity to cosmic antiprotons and to provide leading sensitivity to the low-energy antihelium nuclei in the cosmic radiation. During its pre-flight campaign in Antarctica (November/December 2024), the apparatus was able to perform several muon runs for both scientific and calibration purposes. Performance studies related to the detection of this particle population at sea level are currently being conducted before the scheduled launch during the 2025/26 season.

1. – The physics of GAPS

One of the most profound unsolved questions in modern physics concerns the true nature of Dark Matter (DM) and Dark Energy (DE). According to the latest results from the Planck mission, approximately 68% of the Universe consists of DE, 27% is DM, and only 5% is ordinary (baryonic) matter [1]. Despite this, the origins and fundamental properties of both DM and DE remain elusive. The concept of DM was first introduced by F. Zwicky in 1933, based on his observations of the Coma galaxy cluster, see [2]. Among the various theoretical frameworks proposed to explain DM compelling candidates are Weakly Interacting Massive Particles or WIMPs. In supersymmetric (SUSY) models, the lightest supersymmetric particle (LSP) – such as the neutralino [3] or right-handed sneutrino [4] – has been extensively studied as a candidate for dark matter. Similarly, in theories with extra spatial dimensions, Kaluza-Klein particles, including right-handed neutrinos [5], have been proposed as viable WIMP candidates. Additionally, gravitinos, often referred to as SuperWIMPs due to their extremely weak interactions, emerge as potential dark matter candidates within SUSY frameworks [6]. The General AntiParticle Spectrometer (GAPS) is designed to detect low-energy antiparticles (below ~ 0.25

GeV/n) inside the cosmic radiation. Cosmic-ray antimatter, in fact, provides one of the cleanest channels of indirect DM detection since their natural astrophysical fluxes are low. In particular, the flux of low-energy antideuterons due to DM is expected to be many orders of magnitude above the astrophysical background due to simple secondary production.
The GAPS antideuteron sensitivity is estimated [7] to be 2.0×10^{-6} m^{-2}s^{-1}sr^{-1}(GeV/n)$^{-1}$ summing up all the foreseen three flights of the mission, which is more than two orders of magnitude better than the current upper limit on the flux obtained by BESS-Polar II. This will help probing the validity of various modern DM models.

2. – The GAPS apparatus and its detection technique

The GAPS payload introduces several innovative features with respect to previous detectors. It marks the first use of a lithium-drifted silicon detector (Si(Li)) as a tracker, surrounded by a large Time-of-Flight (TOF) system. The former is composed of ten layers of which seven are active layers, each made up of 10 cm diameter, 2.5 mm thick Si(Li) detectors, segmented into eight strips. Each adjacent tracking layer is separated by 20 cm, with orthogonal strip orientations to allow for an improved spatial tracking. The time-of-flight detector (TOF) is composed of 160 long, thin plastic scintillator paddles ranging in length from 1.5 to 1.8 meters. The paddles are arranged with a slight overlap between adjacent paddles into an inner TOF (the cube, closely surrounding the tracker on all six sides) and the outer TOF (a second layer on top of the cube, called the umbrella, and around the four sides, called the cortina). This arrangement is designed to provide maximum coverage for events stopping in the tracker. The TOF is also used to track the out-going annihilation products, which is crucial for particle identification. [8] A photo of the payload after its integration at the Columbia Scientific Balloon Facility (CSBF) in Palestine, TX, US in June 2024 is depicted in Figure 1.

Fig. 1. – Fully integrated GAPS payload taken in June 2024 (Palestine, TX, US).

GAPS employs a unique technique for identifying antiparticles, which includes energy measurements of both atomic X-rays and charged particles, along with timing and depth of the incoming particles; these combined approaches offer excellent discrimination among antiparticle species. To reach this, the Si(Li) units of the tracking system must serve as both the target material for exotic atom formation and as sensors for detecting both X-rays and particles. The detection principle is based on the fact that, when antiparticles slow down by the energy loss and stop in the target material of the tracker, they will be captured by a silicon atom to form an exotic excited one. This will de-excite, emitting characteristic X-rays, whose energies are different for different antiparticles. After this process, when the antiparticle is in the proximity of a nucleus of silicon or lithium atoms, annihilation occurs, forming a hadron star (mainly secondary pions and protons). Since the mean number of such secondaries is approximately proportional to the number of antinucleons, their multiplicity provides an additional discriminant to identify the impinging antiparticle. This process is illustrated – in a schematic way – in Figure 2, for both an antiproton (left) and an antideuteron (right).

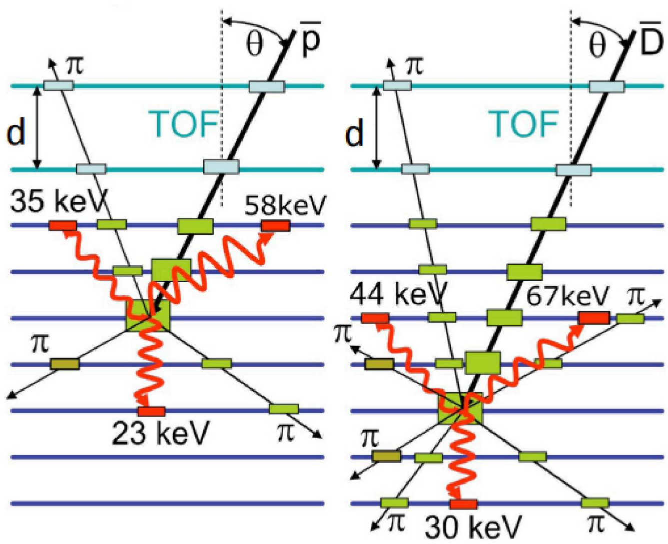

Fig. 2. – A scheme of GAPS detection method. An antiparticle (antiproton on the left and antideuteron on the right) slows down and stops in the Si(Li) target, forming an exotic atom. The atomic keV X-rays are emitted as it de-excites. Afterwards, pions (and protons) are produced during the nuclear annihilation in the hadron star.

3. – GAPS performances in cosmic muon detection

Upon entering the Earth's atmosphere, primary cosmic rays collide with atmospheric nuclei, initiating a chain reaction that produces a shower of secondary, tertiary, and even higher-order particles. As this shower progresses in the vertical direction, the energy of the initial cosmic ray is distributed among an increasing number of daughter particles, causing each one to have lower energy. Muons are primarily generated through the decay of secondary charged pions and kaons and their dominant decay processes are:

$$\pi^{\pm} \to \mu^{\pm}\bar{\nu_{\mu}}(\sim 100\%) \tag{1}$$
$$k^{\pm} \to \mu^{\pm}\bar{\nu_{\mu}}(\sim 63.5\%) \tag{2}$$

The aforementioned muons are the most abundant charged particles that reach the Earth's surface and are unique in their ability to penetrate deeply, due to their relatively low-energy loss in the atmosphere ($\sim$ 2 GeV), long lifetime, and low probability of interaction.
During the GAPS pre-flight campaign in Antarctica, extensive data-runs were performed on the ground. These runs are currently being analyzed to obtain an estimation of the cosmic muon flux at sea level in Antarctica (McMurdo base). This is crucial for various reasons: muons are expected to behave mostly as non-interacting MIP-like particles in the GAPS instrument. This will translate in to clean tracks with a minimum number of secondaries, thus allowing a thorough test of the reconstruction algorithm for single-track events. Though in flight we expect very few muons, the study of such single-track particles is useful to learn how to treat nuclei which are not expecting to show an annihilation signature and will be much more numerous after launch. While protons have traditionally been the dominant background in the search for rare particle species such as antiprotons and antideuterons – both characterized by their interactions in the detector – we have already demonstrated effective control over the proton and alpha components, enabling a more confident identification of these rare signals [9]. Moreover, although muons are unstable particles with a finite lifetime, they are sufficiently long-lived to cross the entire detector, and thus contribute significantly to the background, with rather small effects from solar modulation or solar injections. For this reason, a muon spectrum as a function of energy is a good proxy to assess the stability of the instrument's response over time. Procedures and selection cuts to obtain the cleanest sample of cosmic muons possible are being studied. A 2D display of a single track event is shown in Figure 3. As can be seen, the reconstruction algorithm is working properly, fitting all energy deposits with a single track, as expected from a non-interacting MIP-like particle.

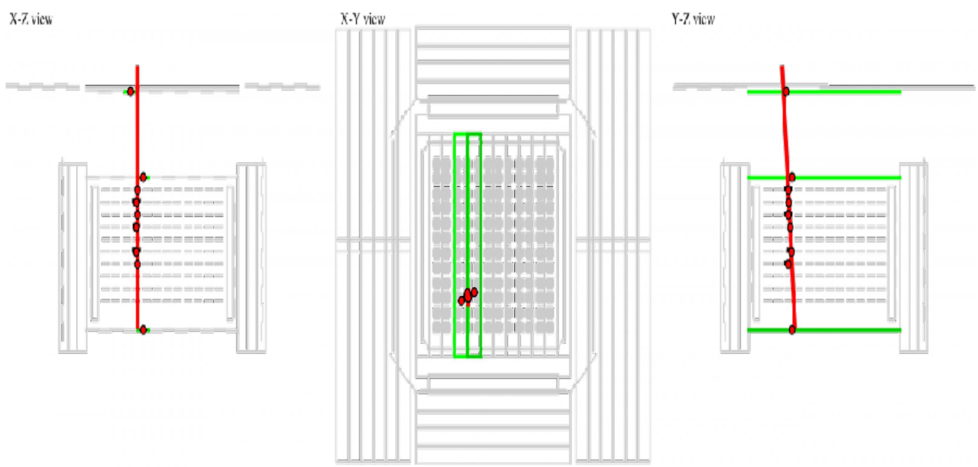

Fig. 3. – 2D event display of a single track event 24/12/13 9:49 am GMT, recorded at LDB (Long Duration Ballon facility).

4. – Conclusions

In December 2024, there have been several launch attempts, all aborted due to anomalous weather conditions leading to adverse and unstable circumpolar winds. After intensive calibration and testing in various institutes and facilities across the US, in advance of its first of three Antarctic flights in the austral summer of 2025, GAPS on-ground data is currently undergoing preliminary analysis to assess the performances of the instrument and its response to various particles.

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