GAPS: Searching for Dark Matter using Antinuclei in Cosmic Rays

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On behalf of the GAPS collaboration
The GAPS experiment

- GAPS is a balloon flight experiment for low energy (<0.25 GeV/n) **antideuteron in cosmic rays** (CRs) that would result from certain dark matter (DM) interactions.

- GAPS will also conduct a high statistics measurement of low energy **antiproton** and will search for **antihelium**.

- The first of a series of flights from Antarctica is expected for late 2021.

- The detector is composed by a ToF system and a Tracker made of 10 plane of SiLi detector.

- GAPS uses a detection technique based on exotic atom formation and subsequent decay and annihilation with X rays and pions emission.
Antimatter production in CRs

a) Primary CRs interacting with interstellar medium (IM)

b) Decay or annihilation of DM particles in galactic halo (beyond standard model theories)

Antimatter from DM is expected to be a significant fraction (antiproton) or higher (antideuteron) with respect to secondaries CRs
Antideuteron production

Secondary antideuteron

CR \rightarrow IM \text{ at rest} \rightarrow \text{Coalescence} \rightarrow \text{at rest}

Primary antideuteron

\text{at rest} \rightarrow \text{Coalescence} \rightarrow \overline{d}

\text{Flux} \quad E (\text{GeV/n})

\text{Few GeV peak}

\text{Ecut} \sim 2 \text{ GeV}

\text{Strongly suppressed below few GeV}

\text{High intensity below few GeV}

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GAPS - antideuteron search
Why antideuteron for DM search?

- Models predict antideuteron from DM decay or annihilation to be order of magnitude higher than the secondaries

Even a single antideuteron detection with GAPS would point to new physics

Antiproton from DM

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Even a single antideuteron detection with GAPS would point to new physics.

- Antiproton signal from dark matter is expected to be a fraction (10-30%) of the secondary from CR interaction.

Possible excess in AMS02 data at 10 GV.
Models predict antideuteron from DM decay or annihilation to be order of magnitude higher than the secondaries. Even a single antideuteron detection with GAPS would point to new physics.

Antiproton signal from dark matter is expected to be a fraction (10-30%) of the secondary from CR interaction.

Antihelium is also expected but with much lower intensity.
GAPS detection technique

**AntiD - antiP identification**

- Time of flight
- Depth - multiple dEdx
- X-rays emission
- Pion multiplicity

Stopping particles inside tracker volume

\[ E_{X\text{-ray}} = (zZ)^2 \frac{M}{m_e} \frac{1}{n_f^2} \left( \frac{1}{n_i^2} - \frac{1}{n_f^2} \right) \]

X-ray emission measured at KEK in 2004/2005

Aramaki et al. Astro.Ph. 49 (2013) 52
Simulated antideuteron event: beta = 0.4

It works in simulation!
Instrument overview

General requirements

- Large acceptance
- Restrictive trigger
- Velocity measurements
- Background rejection
  - X-rays detection
  - Track primary
  - Track secondaries

1 LDB flight (35 days) → high-statistic antiP: 1500 (100< BESS, 7 PAMELA)
3 LDB flights (105 days) → antiD sensitivity: $2 \times 10^{-6} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV/n}^{-1}$

Total mass: 3500 kg
Power: 1.4 kW
TOF system

196 plastic scintillator

16-1.8m

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOF resolution</td>
<td>$\sigma_T &lt; 400$ ps</td>
<td>Laboratory</td>
</tr>
<tr>
<td>Velocity resolution</td>
<td>$\Delta \beta/\beta &lt; 0.12$</td>
<td></td>
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<tr>
<td>Charge resolution</td>
<td>$(\sigma_q)_{68%} &lt; 0.20e$</td>
<td>Initial study</td>
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<tr>
<td>Position resolution</td>
<td>$\sigma_x = 3.0$ cm (length)</td>
<td>Laboratory</td>
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<tr>
<td></td>
<td>$\sigma_y = 4.6$ cm (width)</td>
<td></td>
</tr>
<tr>
<td>Angular resolution</td>
<td>$\sigma_\theta &lt; 3^\circ$ (typical)</td>
<td></td>
</tr>
</tbody>
</table>

Trigger based on:
- **Beta**: rejects high beta particles.
- **Charge**: rejects high Z particles.
- **Hit**: count the number of paddles hit.

Expected Trigger Rates (H, He, C)
- Raw: 82,000 Hz → After cuts: 550 Hz

- Antiprotons Trigger: 36%
- Antideuterons Trigger: 76%
- Proton Rejection Factor: >2500

Si-PMs (x6)
Better performance
Save mass, power, cost

1.8m SiPM paddles
**Tracker system**

**Requirements**
- 4 keV FWHM resolution (100 KeV)
- Large area, relatively high temperature
- Leakage current < 5 nA/strip
- Huge dynamical range (~keV → 100 MeV)
- Low cost, high-yield fabrication process

**Lithium-drifted Silicon**
- Cylindrical detector
- -43°C operational T
- 1100 SiLi detectors
- 10 plane

- 6x6 module each plane
- 8 strips
- 2.5 mm
- 10 cm

**Li ions compensate impurities in boron-doped Si, creating extended charge-free regions**

**Spectrum of $^{241}$Am and $^{109}$Cd at -35°C and -250V Bias**

- Counts [s⁻¹ keV⁻¹]
- Energy [keV]
Simulation and reconstruction

**Fully detector simulation with (GEANT4)**

- Kalman-like filter for primary reconstruction
- Hough transformation for secondaries
- Vertex reconstruction with minimization

Vertex reconstruction based on:

**X-Z view**

**Y-Z view**

**MC event**

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Simulation and reconstruction

Fully detector simulation with (GEANT4)

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X-Z view

Reconstructed event

Y-Z view

Primary

Secondary

05/06/19 GAPS - antideuteron search 14
Reconstruction performances

Vertex resolution

Reconstruction efficiency

Two algorithms for vertex reconstruction now under test

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Acceptance and identification

The main background for antideuteron identification is antiprotons ($\bar{p}/\bar{d} \sim 10^3$)

Identification

Multivariate approach (Likelihood):
- Depth vs beta
- Number of secondaries
- X-rays
- “Calorimetric” approach
  - Total hit number
  - Total energy deposition
  - Energy pattern deposition
  - ...

Neural network (developing)

Machine learning (developing)

Acceptance for antideuterons after applying identification cuts ($10^3$ antiP rejection)

Under study:
Identification using reconstructed variable
GAPS and solar modulation

GAPS will measure antiP - antiD at energies where CRs are heavily affected by solar modulation.

Precise modeling of the solar modulation has to be taken into account to interpret the data.

3D numerical model for CRs propagation inside heliosphere: factor 4 of intensity variation for DM antiD between solar minimum and maximum.
Conclusions

- GAPS will search low energy (<0.25 GeV/n) antideuteron in cosmic radiation as indirect signal of dark matter.

- This is a “background free” channel since the secondary antideuteron from CRs interaction is expected to be orders of magnitude lower.

- Complementary detection technique with respect to magnetic spectrometer with exotic nucleus formation and annihilation.

- GAPS will also perform the highest statistical antiproton measurement at these energies and will search for antihelium.

- Construction is proceeding along with simulation and identification studies.

- First flight late 2021 from McMurdo station.

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