The General AntiParticle Spectrometer - Search for Dark Matter using Cosmic-ray Antinuclei

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• unexplained feature in positrons:
  – astrophysical origin → pulsars
  – SNR acceleration
  – **dark matter annihilation**

• combined fit with antiproton and diffuse gamma-rays from the Galactic Center → 80GeV DM particle?

• understanding astrophysical background is a challenge better constraints on cosmic-ray propagation and astrophysical production are needed
Status Cosmic-ray Antinuclei Searches

- A small $\bar{p}$ excess in AMS-02 data above secondary background predictions at $R \sim 10$ GV was found in various studies → significance level unclear

- AMS-02 reported that several $^{4}\text{He}$ candidate events have been observed → interpretations are actively ongoing

- Antiproton and antihelium both constrain antideuterons → no explanation of antihelium should overproduce antiprotons and antideuterons

- Possible antihelium candidate explanations include:
  - Secondary astrophysical background
  - Dark matter annihilation or decay
  - Nearby antistar: at distance of ~1pc

- Search for antinuclei with independent technique is critical


[Graph depicting antinuclei flux vs kinetic energy]
The GAPS experiment

- The General AntiParticle Spectrometer is the first experiment dedicated and optimized for low-energy cosmic-ray antinuclei search
- Requirements: long flight time, large acceptance, large identification power
- **GAPS will deliver:**
  - a precision antiproton measurement in an unexplored energy range <0.25 GeV/n
  - antideuteron sensitivity 1-2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range
  - provide leading sensitivity to low-energy cosmic antihelium nuclei
- **GAPS is under construction** → first Long Duration Balloon flight from Antarctica in late 2022

mass: ~2,500kg
power: 1.3kW
GAPS Technique

- Antiparticle slows down and stops in material
- Large chance for creation of an excited exotic atom ($E_{\text{kin}} \approx E_I$)
- Deexcitation:
  - Fast ionization of bound electrons (Auger)
  - Complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via characteristic X-ray transitions depending on antiparticle mass
- Nuclear annihilation with characteristic number of annihilation products
GAPS Identification Technique

GAPS identification technique uses:

- Energy loss in the detector of the antinucleus (depends on $Z$ and $\beta$)
- Deexcitation X-rays from exotic atom
- Multiplicity of charged annihilation products
GAPS Antinuclei Sensitivity

- Independent confirmation of magnetometer-based cosmic-ray measurements is critical

- GAPS will provide precision measurement of low-energy antiprotons <0.25GeV/n

- GAPS has 1-2 orders more sensitivity to low-energy antideuterons compared to BESS

- GAPS will also provide precision measurement of low-energy particle fluxes ($p$, $d$, He)

Aramaki et al., Astropart. Phys. 74, 6 (2016)
Korsmeier et al. 2017
GAPS Model Sensitivity

- GAPS is sensitive to a **wide range of dark matter models**, e.g.:
  - Generic 70GeV WIMP annihilation model that explains antiproton excess and $\gamma$-rays from Galactic center
  - Dark matter gravitino decay
  - Extra dimensions
  - Dark photons
  - Heavy DM models with Sommerfeld enhancement
  - Primordial black holes (antiprotons)
GAPS Antihelium Sensitivity

- Finding low-energy antihelium would be truly revolutionary new physics
- More on antihelium with GAPS at COSPAR by Nathan Saffold: H0.2-0015-21

GAPS sensitivity
95\% CL

Dark Matter
- Coogan et al.
  \( m_{\chi\chi \to WW} = 100 \text{ GeV} \)
- Korsmeier et al.
  \( m_{\chi\chi \to b\bar{b}} = 71 \text{ GeV} \)
- Nan Li et al.
  \( m_{\chi\chi \to \eta \bar{s}} = 1 \text{ TeV} \)
- M. Kachelrie\ß et al.
  \( m_{\chi\chi \to \eta \bar{s}} = 100 \text{ GeV} \)
- M. Winkler & T. Linden
  \( m_{\chi\chi \to \phi \bar{b}\bar{b} = 80 \text{ GeV} \)

Background
- Blum et al. (Upper limit)
- Poulin et al.
- A. Shukla et al.
- M. Kachelrie\ß et al.
Tracker

- Tracker acts as target and tracking device
- GAPS will use 1,440 4” Si(Li) detectors, 2.5mm thickness
- Operation at relatively high temp of -35C to -45C, cooling system will use novel OHP approach
- Fabrication scheme developed at Columbia U and MIT, produced by private company Shimadzu, Japan
- Fabrication completed, calibration and flight qualification is ongoing
- Publications:
  - Perez et al., NIM A 905, 12 (2018)
  - Kozai et al., NIM A 947, 162695 (2019)
  - Rogers et al., JINST 14, P10009 (2019)
Time-of-Flight

- **Tasks:**
  - main trigger system, critical to reduce data rate to manageable level (~500Hz)
  - Velocity measurement

- Plastic scintillator: Eljen EJ-200: 160-180cm long, 0.6 cm thick

- SiPM: Hamamatsu S13360-6050VE

- fast sampling with DRS4 ASIC: ~300ps timing resolution end-to-end/$\sqrt{2}$ timing has been demonstrated in the lab
GAPS Path Forward

GAPS is the first experiment optimized specifically for low-energy antiprotons, antideuterons, and antihelium.

GAPS will deliver:
- a precision antiproton measurement in an unexplored energy range <0.25 GeV/n
- antideuteron sensitivity 1-2 orders of magnitude below the current best limits, probing a variety of DM models across a wide mass range
- the only complementary probe of the AMS-02 antinuclei signal

GAPS instrument integration beginning now, on schedule for first science flight from Antarctica in 2022

Additional GAPS talks at COSPAR:
Kozai Masayoshi: PSB.1-0016-21
Nathan Saffold: H0.2-0015-21