Development of the GAPS Experiment for Cosmic-ray Antinuclei Measurements

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Evidence for dark matter

Bullet cluster
red: hot X-ray emitting gas
blue: distribution of dark matter

- dark matter exists, but nature remains unknown!
- luminous matter cannot describe the structure of the Universe
- evidence for dark matter comes from many different type of observations on different distance scales
**Cosmic rays as dark matter messengers**

**conventional cosmic rays**

- primary cosmic rays from star explosions
- interactions with interstellar medium

### Signal

- **new dark matter particles**
- **new physics**
- **known particles**

### Assumption:
- Cosmic rays from dark matter annihilation follow different kinematics than conventional production
- Peak/bump/shoulder on top of conventional spectrum
- Use search channel without strong conventional production: $e^+$, $\gamma$, $\bar{p}$, $\nu$

### Interaction Mechanisms

- Cosmic rays from the annihilation of dark matter
- Conventional cosmic rays
- Photons and neutrinos
- Antiparticles and hadrons
- Conventional production from star explosions
- Interactions with interstellar medium
Dark matter signal in cosmic rays?

- unexplained feature in positrons:
  - astrophysical origin $\rightarrow$ pulsars
    [HAWC excludes some local pulsars]
  - SNR acceleration
  - dark matter annihilation
- combined fit with antiproton and diffuse gamma-rays from the Galactic Center $\rightarrow$ 80GeV DM particle
- understanding astrophysical background is a challenge
- better constraints on cosmic-ray propagation and astrophysical production are needed
Antideuterons as a probe of dark matter

Examples for beyond-standard-model Physics (compatible with p):

**Neutralino:**
SUSY lightest supersymmetric particle, decay into $b\bar{b}$

**late decays of unstable gravitinos**
[Dal & Raklev, Phys. Rev D89, 103504 (2014)]

**astrophysical background:**
collisions of protons and antiprotons with interstellar medium
[Ibarra & Wild, Phys. Rev. D88, 023014 (2013)]

Antideuterons are an important unexplored indirect detection technique!
More antideuteron models

Astrophysical background only:

- All antinuclei species have to be explained together
- Report by AMS-02 of antihelium candidates triggered more theoretical work:
  - evaluate propagation effects
  - nuclear modeling

Dark matter annihilation:

- Blum et al., arXiv:1709.06507
- Tomasetti & Oliva, arXiv:1712.03177
- Lin et al., arXiv:1801.00997
(Anti)deuteron formation

- $d$ ($\bar{d}$) can be formed by an $p$-$n$ ($\bar{p}$-$\bar{n}$) pair if coalescence momentum $p_0$ is small

\[
\gamma_d \frac{d^3 N_d}{dp_d^3} = \frac{4\pi}{3} p_0^3 \left( \gamma_p \frac{d^3 N_p}{dp_p^3} \right) \left( \gamma_n \frac{d^3 N_n}{dp_n^3} \right)
\]

- use an event-by-event coalescence approach with hadronic generators

Aramaki et al., Physics Reports 618, 1 (2016)

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Issues of the coalescence model

- Coalescence uncertainties are about a **factor of 10** on the flux.

- Coalescence is highly sensitive to two-particle correlations between the participating (anti)nucleons (non-pertubative regime).

- Generators not really tuned for antiparticle production
  → Tune with antiproton, deuteron, and antideuteron data
  → Test antiproton spectra first, antineutron data are hard to come by.

- Hadronic generators do not include coalescence formation
  → Added "afterburner".

- Compared simulation results to available data sets (p+p, p+A) → Best-fit coalescence momentum per data set.

- More high statistics data needed to constrain (anti)deuteron coalescence model.
Geomagnetic efficiency

- Earth’s magnetic field deflects charged particles depending on charge and momentum → not every position on orbit sees the same exposure to cosmic rays
- AMS-02 is installed on the ISS (latitude ±52°) → understanding of geomagnetic environment crucial for low rigidities
- GAPS is planned to fly from Antarctica (~-80°) → geomagnetic corrections are minimal
Identification challenge

Required rejections for antideuteron detection:

- protons: $> 10^8 - 10^{10}$
- He-4: $> 10^7 - 10^9$
- electrons: $> 10^6 - 10^8$
- positrons: $> 10^5 - 10^7$
- antiprotons: $> 10^4 - 10^6$

Antideuteron measurement with balloon and space experiments require:

- strong background suppression
- long flight time and large acceptance
The GAPS experiment

- the **General AntiParticle Spectrometer** is specifically designed for low-energy antideuterons, antiprotons and antihelium nuclei

- **GAPS** is under construction → first Long Duration Balloon flights from Antarctica flight 2020
Simulated antideuteron in GAPS

Before the annihilation, an excited exotic atom is formed that is deexcited by X-rays.

Color scale corresponds to deposited energy.
antiparticle slows down and stops in material
large chance for creation of an excited exotic atom \( (E_{\text{kin}} \sim E_{\text{i}}) \)
deexcitation:
- fast ionization of bound electrons (Auger)
  \( \rightarrow \) complete depletion of bound electrons
- Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via characteristic x-ray transitions depending on antiparticle mass

atomic transitions

- Auger e
- refilling e
- \( n_{\text{excite}} \approx \sqrt{\frac{E_{\text{x}}}{m_e}} \)
- \( n = n_{\kappa} \sim 19 \)

p
\( \pi^+ \)
\( \pi^- \)

Nuclear Annihilation
Hadronic annihilation products

- Test of annihilation physics in Geant4 is currently ongoing
- Use antiproton data for validation
- Work with Geant4 developers

Number of charged pions for events that stop in the GAPS tracker material
Identification is a task for multivariate identification techniques:

- Number of tracks from the annihilation vertex
- X-rays in association with nuclear annihilation products
- Total energy deposition of the primary particle
- Column density of material that the antiparticle traversed before stopping
- Total energy deposition from all tracks
- Number of hits in tracker
- Number of hits in TOF
• For the event reconstruction it is critical to identify a well defined primary track → \( \beta \) measurement, energy deposition, column density

• The primary track is used as a seed for the determination of the stopping vertex with the corresponding secondary tracks
GAPS low-energy antiproton

- GAPS will detect ~1000 antiprotons per 30day flight (order of magnitude more than BESS Polar II)
- Antiprotons are essential to:
  - Validate the identification technique
  - Compare with other experiments
  - Estimate antideuteron background
- Antiprotons are sensitive to various DM models: Neutralinos, LZP Gravitinos, primordial black holes
Prototype GAPS [2012]

- demonstrated stable operation of the detector components during flight
- studied Si(Li) cooling approach for thermal model
- measured background levels

![Prototype GAPS Image]

- TOF tracker readout
- 1.2m bus gondola
- X-ray tube
- flight computer

![Graph Image]

- airshower maximum
- float at 33km
- proton
- alpha

2012-06-03 08:10:11
altitude 32.4km
mean TRK T -18.4C

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Development of GAPS
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• High-speed trigger and veto

• 160-180cm long, 0.6 cm thick
• read out both ends with SiPM readout, fast sampling with DRS4 ASIC
  – < 500ps timing resolution end-to-end/√2 timing has been demonstrated in the lab
• Optimization of trigger is ongoing
  – accepts ~80% of antinuclei while reducing proton/alpha rate by $10^3$-$10^4$
• TOF testing and development ongoing:
  – Rev1 testing completed, Rev2 read out board work has started
GAPS will use ~1,000 4” Si(Li) detectors, 2.5mm thick

- Demonstrates required ~4keV energy resolution at relatively high temp of -35 to -45 C
- Fabrication scheme developed at Columbia U and MIT, produced by private company Shimadzu, Japan
- Confirmed performance with cosmic rays (MIPs) and Am-241 source (X-rays)
- Readout via custom ASIC: integrated low-noise preamplifier, dynamic range compression 20keV to ~100MeV
Oscillating heat pipe cooling system

- alternative cooling approach:
  - small capillary metal tubes filled with a phase-changing refrigeration liquid
  - small vapor bubbles form in the fluid
    → expand in warm sections/contract in cool sections
  - rapid expansion and contraction of these bubbles create thermo-contraction hydrodynamic waves that transport heat.
  - no active pump system is required
  - development at JAXA/ISAS

GAPS path forward

● GAPS is specifically designed for low-energetic antideuterons

● all goals for prototype GAPS were met

● currently in finalizing-design phase

● first GAPS science flight from Antarctica 2020

2nd cosmic-ray antideuteron workshop
UCLA, March 27-29, 2019
https://indico.phys.hawaii.edu/e/dbar19
Backup
• propagation is a large uncertainty source for low-energy antideuterons: halo size for diffusion calculation is poorly constrained
• antiproton and positron results tend to exclude MIN halo models and favor larger halo sizes
Si(Li) detector development

- Lithium is applied to the front surface of B-doped p-type Si and diffused through short depth
- Li atoms donate electrons, resulting in an n-type Si lattice layer and leftover free positive Li ions
- under reverse bias, positive Li ions move away from the n-type region
  → compensate acceptor atoms in the p-type bulk
  → compensate impurities in the Si
- drifting procedure creates a thick compensated region (<1.5 days at 500V and 130C)
- ultrasonic machining on the n+(Li) contact → guard ring structure, reduces leakage current, much better energy resolution
- electrodes are thermal-evaporated ohmic/blocking contacts

Perez et al., NIM A 905, 12 (2018)