Antinucleons in Cosmic Rays: Using GAPS to Open New Windows on Dark Matter.

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Assumptions for this talk:

Dark Matter Exists.

(At least some of) It is a WIMP.
A Multimessenger Search

- **Direct Detection**
- **Collider Production**
- **Indirect Detection**

**Photons**
- Galactic Center: High flux, astrophysical background.
- Dwarf Galaxies: Low flux, low/no background.
- Hard to detect, atmospheric background.

**Neutrinos**
- Many pathways, different backgrounds

**Cosmic Rays**
- Galactic Center: High flux, astrophysical background.
- Dwarf Galaxies: Low flux, low/no background.
- Hard to detect, atmospheric background.
Antiprotons ($\bar{p}$)
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Antiprotons ($\bar{p}$)
Why Antideuterons?

Astrophysical Antideuterons
Collision kinematics → Momentum threshold for production.
Low binding energy → inelastic scatter ≈ destruction.

CR → Hadronization → $\bar{p}$ → Coalescence → $\bar{d}$
ISM → other stuff

Graph showing $\phi_{\bar{d}}$ (target) in $10^{-6}$ units as a function of $T_{\bar{p}}$ in GeV/amu.
Why Antideuterons?

Dark Matter Antideuterons
Production is via annihilation or a decay.
→ No kinematic threshold.
→ No low energy cutoff!

Astrophysical Antideuterons
Collision kinematics → Momentum threshold for production.
Low binding energy → inelastic scatter ≈ destruction.

CR          other stuff
            →
Hadronization → \( \bar{p} \) → Coalescence → \( \bar{d} \)

ISM  → \( \bar{n} \)
Significant Ongoing Theoretical Work

Korsmeier, Donato & Fornengo 2018

Tomassetti & Oliva 2017

Blum, Sato & Waxman 2017

Lin, Bi & Yin 2018
Antinucleons provide an excellent window for dark matter searches.

With an almost background free signal they provide a very “clean” window.

However, existing techniques (rigidity based) have problems:

- Energy threshold.
- (Anti)proton suppression.

Solution:

- Exotic atom technique → no background.
- Antarctic balloon → low energy threshold.
Stopping Depth

More likely to stop

→ Slower
Characteristic X-Rays

Simulation checked against data measured at KEK in 2004
Pion & Proton Production

\[ \bar{d} + \text{Atom} \rightarrow \bar{d} + \text{X-Rays} \]

\[ \pi's + p's + \text{stuff} \]

Production $\times$ Efficiency

![Graph showing production efficiency for different $M_{p/\pi}$ values.](image)
Putting It All Together

antiproton

antideuteron

Aramaki+15
(It works in simulations too …)

60 MeV $\bar{p}$
4 pions produced

120 MeV $\bar{d}$
10 pions produced

blue = $\bar{p}$
green = $\bar{d}$
white = pion
yellow = electron
purple = other

antiproton

antideuteron
Predicted Sensitivity

Neutralino

Antiproton flux \([m^2 \cdot s^{-1} \cdot sr^{-1}]\)

- BESS 95/97
- BESS-Polar II
- PAMELA
- GAPS

- primary
- secondary
- primary+secondary

Neutralino

- \(m = 30 \text{ GeV}/c^2\)
- \(m = 8 \text{ GeV}/c^2\)

MED

MIN

AMS 02

\(~1500 \bar{p} \text{ in one flight!}\)

Antideuteron Flux \([m^2 \cdot s^{-1} \cdot sr^{-1} \cdot (GeV/n)]\)

BESS limit 95% C.L.

neutralino (SUSY)

- \(m = 30 \text{ GeV}\)
- gravitino

- \(m = 50 \text{ GeV}\)

LZP (UED)

- \(m_{\chi} = 40 \text{ GeV}\)

astrophys.

background

AMS

AMS

16
Status Update

- NASA funding started 2017.
- Strong and welcome involvement from INFN joining GAPS.
- First flight austral summer 2020-21.
- Now the fun begins:
  - 1350 silicon detectors.
  - ~200 ToF paddles (~400 ends to read out).
  - Trigger & readout electronics.
  - Cooling.
  - Mechanical design.
  - ...

[Diagram showing timeline from 2012 to 2021 with key events such as pGAP flight, Data Analysis, Funding start, CDR, GAPS Integration, and Antarctic Science Flight]
Si(Li) Detectors

- Process developed in partnership with Shimadzu Corp. (Japan).
- Readout ASIC designed by INFN

<table>
<thead>
<tr>
<th></th>
<th>High Gain</th>
<th>Low Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing Resolution</td>
<td>100 ns</td>
<td></td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>4 keV</td>
<td>10%</td>
</tr>
<tr>
<td>Energy Range</td>
<td>20 - 80 keV</td>
<td>0.1 - 100 MeV</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>&lt; -40 ºC</td>
<td></td>
</tr>
<tr>
<td>Leakage Current</td>
<td>&lt; 10 nA</td>
<td></td>
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Perez et al. accepted to NIM A (2018)
Time of Flight (ToF)

Timing Resolution = \((T_A - T_B)/\sqrt{2}\)

1.8m Test Paddle

V2 Preamp Board

V3 Board in Production

PMT
0.48 ns

Hamamatsu R7600-200

3 SiPM
0.34 ns

Hamamatsu S13360-6050CS (LCT5-6050)
Cooling & Mechanical

Oscillating Heat Pipe Cooling System

Carbon Fiber Frame and ToF Supports

Fuke et al. JAI 6(2) 2017
Antinucleons provide a complementary channel for indirect dark matter searches. With a low astrophysical background they have exciting potential for a clean signal.

GAPS will search for low energy antinucleons and provide the best measurement to date of low energy \( \bar{p} \).

The exotic atom technique increases signal purity over rigidity searches.

Scheduled to fly in the austral summer of 2020-21 significant progress has been made.
Backup
Pion Production

(1) Primordial Pion
(2) Direct Emission
Fast Ejectiles
(3) Pre-equilibrium Emission
Fragmentation
(4) Nuclear Evaporation
Slow Ejectiles

Number of $\pi/p$
depend upon nucleon
annihilating

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X-Rays

X-ray energies depend upon exotic atom formed.

GEANT 4 simulation checked against data measured at KEK in 2004

Aramaki+13
\[ \frac{dE}{dX} \]

- More likely to stop
- Slower

![Graph showing probability distribution for antiproton and antideuteron TOF in ns with higher probability for slower TOF values]
Cosmic Rays - Primary Sources

- **Leptons**: Primarily in supernova remnants.
- **Protons**: Primarily in pulsars, their nebulae & binaries.
- **Antiprotons**: Primarily in pulsars, their nebulae & binaries.
- **Probable not a lot**: Antiprotons

**Darks Matter???
Cosmic Rays - Propagation

Leaky Box Model → need size of box and diffusion coefficient

Measure with e.g.:
- Boron-to-Carbon ratio,
- Radioactive isotopes,
- Diffuse radio & $\gamma$-rays
Principle constraint comes from boron-to-carbon ratio \((\propto H^2/D)\).

- H has a strong impact upon relative strength of dark matter signal.
- Typically 3 bounding cases of H, D considered: MIN \((H = 1 \text{ kpc})\), MED \((4 \text{ kpc})\), MAX \((15 \text{ kpc})\).
- MIN is now largely excluded using positron data.

![Graph showing predicted d flux](image-url)
Solar Modulation

Heber+09

Potgieter+15

Differential intensity (particles/MeV/m²/s/sr) vs. Kinetic energy (GeV)

Year vs. Sunspot number and Modulation amplitude

Oulu Neutron monitor

2006b
2007a
2007b
2008a
2008b
2009a
2009b
Cosmic Rays - Secondary Production

\[ p + p \to \bar{p} + p + p + p (+ \text{stuff}) \]
Why Antarctic Balloon?

High = Little Atmosphere

Low Geomagnetic Cutoff

Long Flight Over Land
ToF

UCLA
PMT or SiPM?

Hamamatsu S13360–6050CS (LCT5–6050)

Hamamatsu R7600–200

Si-PM #10683
Low Energy Antinucleons

Rigidity $\propto$ gyro radius

Contamination from other species
Coalescence Momentum

Fitting $p_0$ to data on $d$ production

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Scenario</th>
<th>$\sqrt{s}$ [GeV]</th>
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<tbody>
<tr>
<td>ALICE ($pp$)</td>
<td></td>
<td>7 TeV</td>
</tr>
<tr>
<td>ZEUS ($e^-p$)</td>
<td></td>
<td>318 GeV</td>
</tr>
<tr>
<td>ALEPH (Z decay)</td>
<td></td>
<td>91.19 GeV</td>
</tr>
<tr>
<td>ISR ($pp$)</td>
<td></td>
<td>53 GeV</td>
</tr>
<tr>
<td>BaBar ($e^+e^-$)</td>
<td></td>
<td>10.58 GeV</td>
</tr>
<tr>
<td>CLEO (Y decay)</td>
<td></td>
<td>9.46 GeV</td>
</tr>
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Herwig++ (tuned)
CLEO, ALEPH, ZEUS

PYTHIA 6/8
Herwig++
pGAPS (2012)
Grasp

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anti-$^3$He Sensitivity?

![Graph showing anti-3He sensitivity with various exclusions and annihilation channels.]

- AMS-01 excluded
- PAMELA excluded
- BESS excluded
- AMS-02 reach
- WW annihilation $m=100\text{GeV}$
- $p_0 = 195 \text{ MeV}$
- $p_0 = 300 \text{ MeV}$
- $\text{bb annihilation } m=40\text{GeV}$

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Primordial Black Holes