Antideuterons

Quy Nhon, Vietnam
July 2017

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Diffuse Galactic $\gamma$-ray excess?

Uncovering a gamma-ray excess at the galactic center

- gamma-ray excess at the galactic center → $\sim 30$GeV dark matter particle?
- unresolved millisecond pulsars?
- from pion production in molecular clouds
- tension with dwarf galaxies
- understanding of astrophysical background is a big challenge

Daylan et al., arXiv:1402.6703

Unprocessed map of 1.0 to 3.16 GeV gamma rays

$E^2 dN/dE$ (GeV/cm$^2$/s/sr)
Dark matter signal in positrons?

- Dark matter models are severely constrained:
  - Large cross sections
  - Leptophilic?

- Explained by nearby pulsars producing electrons and positrons?
  - Anisotropy should be smaller than AMS-02 limit, but still measurable with ACTs

- Different acceleration mechanisms

- Important to see how the positron fraction continues

Jin et al., JCAP 1509 (2015) 09, 049

Kopp 2013

Linden & Profumo 2013

P. von Doetinchem

Antideuterons

Jul 17 – p.3
latest AMS-02 antiproton results are also very actively interpreted

discussion is inconclusive if an additional component is needed or not

better constraints on cosmic-ray propagation and astrophysical production are needed
Status of cosmic-ray antideuterons

Antideuterons are the most important unexplored indirect detection technique!

**Examples for beyond-standard-model Physics (compatible with $\bar{p}$):**

- **Neutralino:**
  - SUSY lightest supersymmetric particle, decay into $b\bar{b}$, compatible with signal from Galactic Center measured by Fermi
  - late decays of unstable gravitinos
  - astrophysical background: collisions of protons and antiprotons with interstellar medium

**GAPS and AMS sensitivities are based on simulations**

- **BESS limit 95% C.L.**
- **neutralino (SUSY):**
  - $m_\chi = 30$ GeV
  - $m_{\text{LZP}} = 40$ GeV
  - gravitino (decay) $m = 50$ GeV

+ models with heavy dark matter

**Factors:**

- factor 100

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arXiv:1505.07785
Uncertainties

- dark matter annihilation or decay
- dark matter clumping
- **antideuteron production**
- Galactic propagation
- solar modulation
- **geomagnetic deflection**
- atmospheric interactions
- interactions in detector
Antideuteron formation

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

\[
\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{p_0^3}{6} \frac{m_{\bar{d}}}{m_{\bar{n}} m_{\bar{p}}} \frac{1}{\sqrt{T_{\bar{d}}^2 + 2m_{\bar{d}} T_{\bar{d}}}} \frac{dN_{\bar{n}}}{dT_{\bar{n}}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}}
\]

- Important differences for different experiments and MC generators exist \( \rightarrow \) more data needed
Issues of the coalescence model

• phase space for ion production depends on the available energy in the formation interaction

• coalescence is highly sensitive to two-particle correlations between the participating (anti)nucleons → no a-priori reason to expect two-particle correlations from one generator to be more reliable than from another

• spatial separation → antinucleons originating from weakly decaying particles with macroscopic decay lengths are produced too far from the primary interaction vertex

• 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

• formation probability in the per-event simulation coalescence approach is taken to be exactly 100%, e.g., spin is not considered

• I do not know any hadronic generator that includes coalescence → construct “afterburner”
- coalescence afterburner added to EPOS-LHC, Geant4
- more data needed to constrain (anti)deuteron coalescence model
• multi-purpose, fixed-target experiment at the CERN SPS (NA61/SHINE facility paper: JINST 9 (2014) P06005)
  • precise measurements of properties of produced particles: q, m, p
• cosmic-ray antideuteron production happens between 40 and 400GeV
  • SPS energies from 9 to 400GeV are ideal
• data under discussion from the NA61/SHINE strong interactions program:
  • p+LH data taken at 13, 20, 31, 40, 80,158GeV/c + 400GeV/c (2016)

- high momentum resolution: \( \sigma(p)/p^2 \approx 10^{-4} \) (GeV/c)^{-1} (at full B=9Tm)
- ToF walls resolution:
  • ToF-L/R: \( \sigma(t) \approx 60 \) ps
  • ToF-F: \( \sigma(t) \approx 120 \) ps
- Good particle identification:
  • \( \sigma(dE/dx)/<dE/dx> \approx 0.04 \)
  • \( \sigma(minv) \approx 5 \) MeV
- high detector efficiency: > 95%
- event rate: 70Hz
reverse computation of antiproton trajectories starting at the same location with different rigidities
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change in magnetic environment changes the trajectories drastically → changes geomagnetic cutoff values
Cutoff comparison of different trajectories

- average geomagnetic cutoff efficiency depends on flight location (LDB = antarctic trajectory, ULDB = COSI flight from Wanaka, New Zealand)
- antiprotons less suppressed for Antarctic trajectory
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
AMS-02 antideuteron analysis

<table>
<thead>
<tr>
<th>e^-</th>
<th>p</th>
<th>He, Li, Be, ...Fe</th>
<th>γ</th>
<th>e^+</th>
<th>p, d</th>
<th>He, C</th>
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<tbody>
<tr>
<td>TRD</td>
<td>γ=E/m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOF</td>
<td>dE/dx, velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracker</td>
<td>dE/dx, momentum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RICH</td>
<td>precise momentum</td>
<td></td>
<td></td>
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<tr>
<td>ECAL</td>
<td>shower shape, energy det.</td>
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</tbody>
</table>

• **antideuteron identification:**
  – momentum measured in the form of rigidity
  – charge from TOF, TRD, tracker
  – lower velocities: Time Of Flight scintillator system
  – higher velocities: Ring Image Cherenkov detector

• **self-calibrated analysis:**
  – calibrate antideuteron analysis with deuterons and antiprotons (simulations and data)

- **analysis is ongoing**
The GAPS experiment

- the General AntiParticle Spectrometer is specifically designed for low-energy antideuterons and antiprotons
- Long Duration Balloon flights from Antarctica
- identification by stopping and creation of exotic atoms tested in KEK testbeam measurements: Astropart. Phys. 49, 52 (2013)
- GAPS has been approved by NASA & JAXA → first flight 2020

GAPS has a length of 3.6m, a width of 3m, and a weight of 1700kg. It is equipped with TOF with PMT or SiPM readout. It contains approximately 1350 Si(Li) wafers and has a power consumption of 1.4kW (Si(Li) 600W, TOF 400W).
GAPS sensitivity

Background rejection:

- stopping protons don't have enough energy to produce pions and cannot form exotic atoms (pos. charge)
- deexcitation X-rays have characteristic energies
- number of annihilation pions and protons
- stopping depth in detector

Aramaki et al., Astropart. Phys. 74, 6 (2016)
Predicted primary antiproton fluxes from:

- Neutralinos
- LZP
- Gravitinos
- primordial black holes (PBHs), along with neutralino signals

as seen by 1 GAPS LDB flight.
GAPS will use ~1350 4” Si(Li) detectors, 2.5mm thick
- fabrication scheme developed at Columbia U, produced by private company Shimadzu, Japan
- confirmed performance with cosmic rays (MIPs) and Am-241 source (X-rays)

TOF testing and development ongoing → decision between PMTs and SiPms
Next up: antihelium?

- AMS-02 announced antihelium candidates
- needs more data over the next years to make a statistically sound statement
- has important implications for antiprotons and antideuterons
  → all three channels have to be explained at the same time
  → nuclear formation is a key issue
Postdoc openings for GAPS

**Position**

**Hawaii U. - Postdoc**

**Field of Interest:** astro-ph, hep-ex

**Experiment:** GAPS

**Deadline:** 2017-07-31

**Region:** North America

**Job description:**

**Duties and Responsibilities:**
The successful candidate will participate in the balloon-borne cosmic-ray antideuteron experiment GAPS. Cosmic-ray antideuterons are an important new probe for indirect dark matter identification. Detailed design and construction of the payload will start in 2017 and the first flight from Antarctica is planned for the end of 2020. The Hawaii group is mainly involved in the simulation tools and analysis software development as well as the calibration and qualification of lithium-drifted-silicon detectors.

**Minimum Qualifications:**
Applicants must hold a doctoral degree, preferably in (astro)particle physics. Extensive experience with simulation tools (Geant4) and data analysis (ROOT) as well as hands-on lab experience with solid-state particle physics detectors is expected.

**To Apply:**
Send application (cover letter, curriculum vitae, list of publications, and contact information for at least two references) to philipvd@hawaii.edu. Please specify in the subject of the email Postdoctoral fellow for the GAPS experiment.

**Position also open at UCLA:**

http://inspirehep.net/record/1505690

http://inspirehep.net/record/1495582

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Antideuterons
Conclusion & Outlook

- antideuteron searches are experimentally challenging
  → multiple experiments for cross-checks are important

- AMS-02 and GAPS have very different event signatures AND very different backgrounds
  → very good for independent confirmation

- measurements with NA61/SHINE will improve understanding of antideuteron production and modeling

- measurement of antideuterons is a promising way for indirect dark matter search