Dark matter identification with cosmic-ray antideuterons

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Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuterons

under review at Physics Reports: arXiv:1505.07785
Dark matter signal in cosmic rays?

- unexplained features in positrons
- proposed theories:
  - astrophysical origin → pulsars
  - SNR acceleration
  - dark matter self-annihilation
- gamma-ray excess at the galactic center
  → 30GeV dark matter particle?
- No (?) excess for antiprotons → inconclusive

Daylan et al., arXiv:1402.6703
Jin et al., arXiv:1410.0171
Giesen et al., arXiv:1504.04276
Status of cosmic ray antideuterons

**Examples for beyond-standard-model Physics:**

- **Neutralino:**
  - SUSY lightest supersymmetric particle, decay into $bb$, compatible with signal from Galactic Center measured by Fermi
  - late decays of unstable gravitinos
    - $\rightarrow$ Timur Delahaye

- **astrophysical background:**
  - collisions of protons and antiprotons with interstellar medium

- **+ models with heavy dark matter**

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Antideuterons are the most important unexplored indirect detection technique!
Uncertainties

- Dark matter annihilation or decay
- Dark matter clumping
- **Antideuteron production**
- **Galactic propagation**
- Solar modulation
- **Geomagnetic deflection**
- Atmospheric interactions
- Interactions in detector

Modulation by solar wind

Deflection in magnetic field

Scattering in magnetic fields, interaction with interstellar medium

Zoom

20GeV proton

Proton > 10MeV red
Electron > 10MeV green
Positron > 10MeV blue
Neutron > 10MeV turquoise
Muon > 10MeV magenta
Photon > 10keV yellow

Interactions with atmosphere
Antideuteron formation

- antideuterons can be formed by an antiproton-antineutron pair if relative momentum is small (coalescence momentum $p_0$)

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

- important differences for different experiments and MC generators exist → more data would help
Coalescence uncertainty

• improvement during the last years using tools like Pythia and Herwig for hadronization:
  – produce antiprotons and antineutrons
  – respect jet structure
  – antiproton and antineutron have to be close in space and momentum space
Antideuterons and NA61/SHINE

- Fixed target experiment: main motivation is QCD phase transition, but NA61 also has “customers“ from the UHECR and neutrino community
- Cosmic-ray production happens between 40 and 400 GeV → SPS energies from 9 to 400 GeV are ideal
- proton-proton interactions with incident momentum between 13 and 158 GeV/c were already recorded in 2011
- 350GeV $p-p$ run this fall → now
Propagation is a large uncertainty source for low-energy antideuterons: *halo size for diffusion calculation is poorly constrained*

- More data on different cosmic nuclei are needed (and hope that they do not need more complicated modeling for interpretation!)
• Simulations with IGRF geomagnetic field and Tsyganenko 2001 magnetosphere
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

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<th>e^-</th>
<th>p</th>
<th>He, Li, Be,..Fe</th>
<th>γ</th>
<th>e^+</th>
<th>p, d</th>
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- **Operating on the ISS since 2011**
- **antideuteron identification:**
  - 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)
  - geomagnetic cut-off and solar effects: study much more abundant low-energy protons, antiprotons, and deuterons for calibration

\[
m = R \cdot Z \sqrt{\frac{1}{\beta^2} - 1}
\]
The GAPS experiment

- the **General AntiParticle Spectrometer** is especially designed for low-energy antideuterons and antiprotons
- identification by stopping and creation of an exotic atom
  - [KEK testbeam measurements → Astropart. Phys. 49, 52 (2013)]
- all prototyping is done
- LDB flights from Antarctica proposed

![Diagram of the GAPS experiment](image)

- Plastic Scintillator
- Si(Li) Layer
- X-ray
- π⁺, π⁻, and p trajectories
- Exotic Atom
- Plastic scintillators with PMT readout
  - weight: 1700kg
  - power: 1.4kW
  - readout: ~100mW/ch (preamp: ~15mW/ch)
- ~1400 Si(Li) wafers

**Notes:**
- P. von Doetinchem
- Columbia U, UC Berkeley
- UCLA, U Hawaii, Haverford
- Sep 15 – p.13
Complementarity

- antideuteron search is experimentally challenging
  → multiple experiments for cross-checks are very important

- AMS-02 and GAPS have very different event signatures AND very different backgrounds
  → very good for independent confirmation
  (see also direct dark matter searches with different approaches)

- two independent flight trajectories → different geomagnetic cut-off locations
  - ISS is at a maximum of ±52deg
  - GAPS would fly at ~-80deg

- low-energy antiproton flux measurement will be the most important cross-check between AMS-02 and GAPS
Conclusion

- measurement of antideuterons is a promising way for indirect dark matter search
- AMS on the ISS is currently the best instrument for the study of antideuterons
- future GAPS is specifically designed for low-energetic antideuterons
- more exchange between theory and experiments: We started a bigger community effort last year!