Dark matter identification with cosmic-ray antideuterons

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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

Jin et al., arXiv:1410.0171
Daylan et al., arXiv:1402.6703
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 → Timur Delahaye

astrophysical background:
collisions of protons and antiprotons with interstellar medium + models with heavy dark matter

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

scatter in magnetic fields, interaction with interstellar medium

proton > 10MeV red
electron > 10MeV green
positron > 10MeV blue
neutron > 10MeV turquoise
muon > 10MeV magenta
photon > 10keV yellow

zoom

20GeV proton

interactions with atmosphere
Antideuteron formation

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

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

- Important differences for different experiments and MC generators exist → 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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- 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
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!