The need for antideuteron production cross section measurements

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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
Status of cosmic ray antideuterons

Examples for beyond-standard-model Physics:

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

Antideuterons are the most important unexplored indirect detection technique!
### AMS antideuteron analysis

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<th>p</th>
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**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

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

**self-calibrated analysis:**

- Calibrate antideuteron analysis with deuterons and antiprotons (simulations and data)
- Geomagnetic cut-off location is challenging: study low-energy protons and electrons to calibrate geomagnetic and solar effects
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)]
- LDB flights from Antarctica
Antideuteron formation

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

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

- Coalescence does not affect antiproton/proton ratio → break degeneracy of antiproton and antideuteron
Antideuteron formation

Source spectrum $Q_{sec}^{Td}(T_{d})$

- major conventional production mechanisms of cosmic rays with ISM protons at rest:
  - $p+p \rightarrow \bar{d}+X$ (threshold 17GeV)
  - $\bar{p}+p \rightarrow \bar{d}+X$ (threshold 7GeV)

  $\rightarrow$ threshold is much lower
  $\rightarrow$ antiprotons are important
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

- Important differences for different experiments and MC generators exist!
What is going on?

(1) Antideuteron production depends on the exact underlying process and the available center of mass energy:

- Cosmic-ray antideuteron production is most likely dominated by the production relatively close to the threshold (anti-correlation due to phase space considerations of antiprotons and antineutrons important)
- Different values of $p_0$ for different dark matter masses and different contributing background processes might be the right approach
- What is best value?
  → $Z$ resonance (100GeV DM) or $\Upsilon$ resonance (10GeV DM)?
  → Different values for DM and astrophysical background?

(2) Monte Carlo generators are not reliable enough:

- Generators not really tuned for antiparticle production
- Tune with antiproton and deuteron data

Event-by-event coalescence model approach has to be validated against more data to reduce the production uncertainty for the cosmic ray antideuteron interpretation
Alternatives to coalescence model

- Heavy-ion collisions well-described in thermal model:

\[
\frac{dN}{dy} \approx \exp \left( -\frac{m}{T_{\text{chem}}} \right)
\]

- Antideuterons directly produced in thermal freeze-out or at a later stage via coalescence?

- Random event normalized to experimental data:

\[
\sigma_{\vec{p}n \rightarrow \vec{d}X \left( |\vec{p}_{\vec{p}} - \vec{p}_{\vec{n}}| \right)} = \sigma_0 \text{free parameter}
\]

- For coalescence $|\vec{p}_{\vec{p}} - \vec{p}_{\vec{n}}|$ is typically 100-200MeV and for this new model $\sim$1GeV → allows $\Delta$-resonance production
antideuteron production in hadronic decays of Y resonances (Y(nS), n=1,2,3)
potentially very interesting for low-mass dark matter

\[
\frac{\sigma \left( e^+ e^- \rightarrow \bar{d}X \right)}{\sigma \left( e^+ e^- \rightarrow \text{hadrons} \right)} = (3.01 \pm 0.13^{+0.37}_{-0.31}) \cdot 10^{-6}
\]
• *pp* is main process for antideuteron production by cosmic-ray spallations
• *p*-Pb and Pb-Pb collisions are less relevant for studies of cosmic antideuterons due to the different dynamics
• *d/p* ratio determined by event multiplicity
  → goes in saturation for Pb-Pb (higher nucleon multiplicity vs. increasing volume)
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 and also 60GeV $p$-$C$
NA49 antideuterons

- NA49 is pre-decessor experiment

- NA49 lead-lead data were already analyzed for antideuterons

- Important cross-check for the MC generators: measurement of the yield of antiprotons with the same data

- Could in principle also select incident antiprotons

upcoming PANDA experiment at the FAIR collider in Darmstadt, Germany will study the interactions of a 1.5-15 GeV antiproton beam with different targets (e.g., hydrogen, deuterium, gold, etc.)

prominent antideuteron production channel: $\bar{p}p \rightarrow \bar{d}X$
Antideuteron production with EPOS-LHC MC

- Also production of antideuterons in collisions with heavier ions important for \( p(\bar{p}) \) interactions with detector materials or with the atmosphere

- EPOS-LHC has been optimized/tuned in recent years to describe minimum bias LHC events (\( p-p \), \( p-Pb \), \( Pb-Pb \))
- Not a lot/only quite old data available → NA61 has more data on disk already

- Collaborators at UNAM, Mexico from ALICE: D. Gomez, A. Menchaca, V. Grabski

Geant4 - Model for $\bar{d}$ simulation

- recent implementation in Geant4: antideuteron simulations

- FTF model (diffractive string excitation with momentum transfer) was extended to handle nucleus-nucleus interaction down to 0GeV

- best model for antiprotons, antineutrons, antideuterons:
  - very little data for validation available
  - needed:
    - antideuteron formation
    - exotic model for antiproton and antideuteron (GAPS)

Galoyan, Uzhinsky arXiv:1208.3614
\( p \) and \( d \) production in \( p\)-He with Geant4

- test of Geant4 physics for \( p\)-He production “as is” for different models
- average yield for 8g/cm\(^2\) of helium

\[ \rightarrow \text{if all the traversed matter in ISM for cosmic rays would be helium} \]
\( p \) and \( d \) production in \( p\)-He with Geant4

- antiproton and deuteron models show different energy peaks, steepness, and yield
- I have to understand more which model is preferred and describes the data the best
Conclusion & Outlook

- Measurement of antideuterons is a promising way for indirect dark matter search
- Antideuteron production is an important uncertainty
- More experimental data are needed
- Extended models and improved simulation tools needed
- Measurements with NA61/SHINE and hopefully PANDA will improve understanding of antideuteron production and modeling

AMS on ISS

GAPS from Antarctica

~13m

vertex time projection chamber 1

vertex time projection chamber 2

main time projection chamber left

main time projection chamber right

trigger scintillator counter

gap time projection chamber

vertex magnets

time of flight left

time of flight right

time of flight forward

projectile spectator detector

trigger scintillator counter

PANDA