New estimation of the secondary antideuteron cosmic-ray flux

Diego Gomez Coral
Instituto de Física, UNAM

2th Cosmic-ray Antideuteron Workshop
Indirect dark matter searches

Expected antideuteron production in cosmic-ray interactions

Primary cosmic rays from SNRs

Interaction with the ISM

\[ \bar{p}, N, \nu, \gamma \]

\[ \bar{p}, \bar{n}, \bar{d} \]

Hypothetical antideuteron cosmic-rays from dark matter

Dark matter candidates

DM

\[ W, Z, q... \]

\[ d, \bar{d} \text{ are formed after hadronization} \]

\[ W, Z, q... \]
Antideuteron CRs simulation

Indirect dark matter searches

Examples of antideuteron signals from dark matter candidates interactions.

Late decays of unstable gravitinos

Neutralino: SUSY lightest supersymmetric particle, decay into $bb$

Astrophysical background: Cosmic-ray collisions with the interstellar medium

Antideuterons are an important unexplored indirect detection technique.

Antideuteron formation model

Coalescence Model

Deuterons and antideuterons can be formed by a pair p-n or p-n close in phase space.

\[
\gamma_d \frac{d^3 N_d}{dp_d^3} = \frac{4\pi}{3} p_0^3 \left( \gamma_p \frac{d^3 N_p}{dp_p^3} \right) \left( \gamma_n \frac{d^3 N_n}{dp_n^3} \right)
\]

\(p_0\) is extracted from this comparison

Collisions are simulated with Monte Carlo generators, to produce p-n and p-\(\bar{\text{n}}\) pairs.

Afterburner

d and \(\bar{d}\) are created from the pairs event by event.

The results from simulations are compared to data.
Antiproton production simulation

• To generate a correct prediction of antideuterons using MC, it is necessary to have a proper description of antiprotons.

• High energy MC are suggested by M. Kachelriess et al. 2015.

![Invariant differential cross section for antiprotons in p+p collisions at 158 GeV/c, as function of rapidity](image)

Proton and antiproton data list on p+p and p+A collisions to be compared to simulations. D. Gomez-Coral et al. 2018.
Antiproton production simulation

- The most reliable MC model is selected from the comparison to data.

\[
\Delta = \frac{E_{\frac{d\sigma}{dp}}^{\text{sim}} - E_{\frac{d\sigma}{dp}}^{\text{data}}}{\sqrt{(\epsilon_{\text{sim}})^2 + (\epsilon_{\text{data}})^2}}
\]
Antideuteron production simulation

- The coalescence momentum ($p_0$) is determined from the fit of simulations to data.

<table>
<thead>
<tr>
<th>Experiment or Laboratory</th>
<th>Reference</th>
<th>Collision</th>
<th>$p_{lab}$ (GeV/c)</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>No. of points</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN</td>
<td>[194]</td>
<td>p+p</td>
<td>19</td>
<td>6.15</td>
<td>6</td>
</tr>
<tr>
<td>CERN</td>
<td>[194]</td>
<td>p+p</td>
<td>24</td>
<td>6.8</td>
<td>4</td>
</tr>
<tr>
<td>Serpukhov</td>
<td>[198]</td>
<td>p+p</td>
<td>70</td>
<td>11.5</td>
<td>7</td>
</tr>
<tr>
<td>CERN-SPS</td>
<td>[200, 205]</td>
<td>p+Be</td>
<td>6</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>p+Be</td>
<td>200</td>
<td>19.4</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p+Al</td>
<td>300</td>
<td>23.8</td>
<td>3</td>
</tr>
<tr>
<td>Fermilab</td>
<td>[203]</td>
<td>p+Be</td>
<td>1497.8</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>CERN-ISR</td>
<td>[206, 207, 208]</td>
<td>p+p</td>
<td>1497.8</td>
<td>53</td>
<td>3</td>
</tr>
<tr>
<td>CERN-ALICE</td>
<td>[155, 209]</td>
<td>p+p</td>
<td>$4.3 \times 10^5$</td>
<td>900</td>
<td>3</td>
</tr>
<tr>
<td>CERN-ALICE</td>
<td>[155, 209, 210]</td>
<td>p+p</td>
<td>$2.6 \times 10^7$</td>
<td>7000</td>
<td>21</td>
</tr>
</tbody>
</table>

Deuteron and antideuteron data list on p+p and p+A collisions to be compared to simulations. D. Gomez-Coral et al. 2018.

Antideuteron invariant differential cross section in p+p collisions at 70 GeV/c, as function of $p_T$.
Antideuteron production simulation

$p+p$ at $\sqrt{s} = 53$ GeV

Antideuteron invariant differential cross section as function of $p_T$ compared to ISR data.

$p+p$ at $\sqrt{s} = 900$ GeV

Antideuteron invariant differential cross section as function of $p_T$ compared to ALICE-LHC data.
Coalescence momentum ($p_0$) and production cross section

- $p_0$ is parameterized as function of the projectile kinetic energy.
- $p_0$ is similar for $p+p$ and $p+Be$ collisions.

$\text{p+p} \rightarrow X + \text{d}

\text{bar}$
Antideuteron source term

\[ q_d^{sec}(E_{kin}^d) = \sum_{i=p,He,p} \sum_{j=p,He} 4\pi n_j \int_{T_{min}}^{\infty} dT_i \left( \frac{d\sigma}{dE_{kin}^d} \right) \Phi_i(T_i) \]

EPOS-LHC cross-section

p, He Fluxes

Antideuteron CRs simulation
Antideuteron source term

- Proton and helium fluxes with and without hardening are inserted in the convolution.

- Hardening increases dbar flux by less than 10%.
- dbar production is higher than in previous works.
# Propagation with Galprop56

## Set 1 DR
**Without convection**

<table>
<thead>
<tr>
<th>$z$ [kpc]</th>
<th>$D_0/10^{28}$ [cm$^2$ s$^{-1}$]</th>
<th>$\delta$</th>
<th>$V_{\text{alf}}$ [km s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>4.37</td>
<td>0.494</td>
<td>7.64</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proton</th>
<th>Helium</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>5.78 GV</td>
</tr>
<tr>
<td>R2</td>
<td>304 GV</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>1.74</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>2.35</td>
</tr>
<tr>
<td>$\gamma_3$</td>
<td>2.178</td>
</tr>
</tbody>
</table>

## Set 2 DCR
**With convection**

<table>
<thead>
<tr>
<th>$z$ [kpc]</th>
<th>$D_0/10^{28}$ [cm$^2$ s$^{-1}$]</th>
<th>$\delta$</th>
<th>$V_{\text{alf}}$ [km s$^{-1}$]</th>
<th>$V_{\text{conv}}$ [km s$^{-1}$]</th>
<th>$dV/dz_{\text{conv}}$ [km s$^{-1}$ kpc$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.3</td>
<td>0.395</td>
<td>28.6</td>
<td>12.4</td>
<td>10.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R1</th>
<th>R2</th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
<th>$\gamma_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 GV</td>
<td>360 GV</td>
<td>1.69</td>
<td>2.44</td>
<td>2.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R1</th>
<th>R2</th>
<th>$\gamma_1$</th>
<th>$\gamma_2$</th>
<th>$\gamma_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 GV</td>
<td>330 GV</td>
<td>1.71</td>
<td>2.38</td>
<td>2.21</td>
</tr>
</tbody>
</table>

---

*T. A. Porter et al., 2017*

*M. J. Boschini et al 2017 PoS(ICRC2017)278*
Proton and Helium fluxes

\[ \Phi_p \times E^{2.7} \] for proton fluxes and \[ \Phi_{He} \times E^{2.7} \] for helium fluxes, with kinetic energy per nucleon \( E_{\text{kin}} \) in [GeV/n].

- Set 1 (\( \phi_F = 570 \text{ MeV} \))
- Set 2 (\( \phi_F = 570 \text{ MeV} \))
- Proton data AMS-02

Relative difference shown with shaded regions.
Secondary Antideuteron Flux

Adiabatic energy loss

Maximum is shifted.
Increase at high energy.

Flux $\Phi_d$ [m$^2$ s sr GeV/n$^{-1}$] vs Kinetic energy per nucleon $E_{\text{kin}}$ [GeV/n]

- GAPS
- AMS-02
- AMS-02

MED propagation $\phi_F = 500$ MeV
- EPOS-LHC+GALPROP set1
- EPOS-LHC+GALPROP set2
- Ibarra et al.
- Donato et al.
- Duperray et al.
Summary

- A new study on the secondary antideuteron production was presented, using a high-energy MC generator (EPOS-LHC) and the coalescence model.

- Simulations were compared to an extensive data set, including new measurements from NA61 and ALICE-LHC.

- From the comparison to data, it seems the coalescence momentum ($p_0$) depends on the collision energy. As consequence:
  - Antideuteron production cross section shows important differences with respect to previous calculations.
  - Antideuteron flux maximum is shifted and it increases above 4 GeV/n in comparison with other works.
Thank you!
Boron to Carbon ratio

Set1 ($\phi_F = 570$ MeV)
Set2 ($\phi_F = 570$ MeV)

data AMS-02

Kinetic energy per nucleon $E_{\text{kin}}$ [GeV/n]
Antiproton production simulation