Where do AMS-02 anti-helium events come from?

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w/ P. Salati, I. Cholis, M. Kamionkowski and J. Silk


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Anti-helium in AMS data?

Latest results from the AMS Experiment

Observation of anti-He events

Charge = -2
Mass = 2.96 ± 0.33 GeV/c²
Charge (He) = +2
Mass (³He) = 2.83 GeV/c²

July 11, 2019
EPS-HEP Conference 2019
Ghent, Belgium

A. Kounine / MIT
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Massive Monte Carlo simulations are carried out to evaluate significance: AMS sensitivity $\sim 5\times10^{-10}$

Kounine, ICRC 2011
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Current event rate is $\sim 20$ times above the claimed sensitivity. 

*Kounine, ICRC 2011*
Secondary cosmic-ray anti-helium

$$q_{\text{sec}}(\overline{\text{He}} | E_{\overline{\text{He}}}, x) = \sum_{i \in \{p, \alpha\}} \sum_{j \in \text{H, He}} 4 \pi \int dE_i \Phi_i(E_i, x) n_j(x) \frac{d\sigma_{ij \rightarrow \overline{\text{He}}}}{dE_{\overline{\text{He}}}}(E_i, E_{\overline{\text{He}}})$$

Fusion of $p$ & $n$
Coalescence factor $B$

Solar modulation with $\phi^F_p \neq \phi^F_p$
The coalescence factor

\[ \text{coalescence} \equiv \text{fusion of } \bar{p} \& \bar{n} \text{ into } \bar{d}, \, ^3\text{He} \text{ or } ^4\text{He} \]

\[ 2\Delta = k_1 - k_2 \]

coalescence momentum \( p_0 = p_{\text{coal}}/2 \)

\[ d^3N_{\bar{d}}(K) = \int d^6N_{\bar{p},\bar{n}} \{ k_1, k_2 \} \times C(\Delta) \times \delta^3(K - k_1 - k_2) \]

\[ B_2 = \frac{E_{\bar{d}}}{E_{\bar{p}} E_{\bar{n}}} \int d^3\Delta \, C(\Delta) \sim \frac{m_{\bar{d}}}{m_{\bar{p}} m_{\bar{n}}} \left\{ \frac{4}{3} \pi p_0^3 = \frac{\pi}{6} p_{\text{coal}}^3 \right\} \]

Coalescence factor \( B_2 \)

\[ \frac{E_{\bar{d}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{d}}}{d^3K} = B_2 \left\{ \frac{E_{\bar{p}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{p}}}{d^3k_1} \right\} \left\{ \frac{E_{\bar{n}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{n}}}{d^3k_2} \right\} \]

Courtesy Pierre Salati
The coalescence factor

coalesscence ≡ fusion of $\bar{p} & \bar{n}$ into $\bar{d}, \bar{3He}$ or $\bar{4He}$

$2\Delta = k_1 - k_2$

coalescence momentum $p_0 = p_{coal}/2$

Production on anti-nuclei with mass $A$

$$\frac{E_A}{\sigma_{in}} \frac{d^3\sigma_A}{d^3k_A} = B_A \left\{ \frac{E_p}{\sigma_{in}} \frac{d^3\sigma_p}{d^3k_p} \right\}^Z \left\{ \frac{E_n}{\sigma_{in}} \frac{d^3\sigma_n}{d^3k_n} \right\}^{A-Z}$$

with $k_p = k_n = k_A/A$

Coalescence factor $B_A$

$$B_A = \frac{m_A}{m_p m_n^{A-Z}} \left\{ \frac{\pi}{6} p_{coal}^3 \right\}^{A-1}$$

Courtesy Pierre Salati
Determination of the coalescence momentum

Monte Carlo simulations show different results depending on simulator / data sets / $\sqrt{s}$

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**Fitting $p_0$ to data on $\bar{d}$ production**

<table>
<thead>
<tr>
<th>Simulator/Process</th>
<th>Data Set</th>
<th>$\sqrt{s}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herwig++ (tuned)</td>
<td>Cleo, ALEPH, ZEUS</td>
<td>7 TeV</td>
</tr>
<tr>
<td>ALICE ($pp$)</td>
<td></td>
<td>318 GeV</td>
</tr>
<tr>
<td>ZEUS ($e^-p$)</td>
<td></td>
<td>91.19 GeV</td>
</tr>
<tr>
<td>ALEPH ($Z$ decay)</td>
<td></td>
<td>53 GeV</td>
</tr>
<tr>
<td>ISR ($pp$)</td>
<td></td>
<td>10.58 GeV</td>
</tr>
<tr>
<td>BaBar ($e^+e^-$)</td>
<td></td>
<td>9.46 GeV</td>
</tr>
</tbody>
</table>

---

**Graph**

- **FTFP-BERT**
  - $p+p$
  - $p+\text{Be}^+$
  - $p+\text{Al}^+$

- **EPOS-LHC**
  - $p+p$
  - $p+\text{Be}^+$
  - $p+\text{Al}^+$

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**References**

- Dal & Raklev, *PRD* 89 (2014)

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© Pierre Salati

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Gomez-Coral ++ *PRD* 98 (2018)

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V. Poulin - LUPM (CNRS)

EPS HEP, Ghent - 12/07/19
Collaborations (e.g. Alice) provide us with measurements of the coalescence factor $B$

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left( E_p \frac{d^3N_p}{dp_p^3} \right)^Z \left( E_n \frac{d^3N_n}{dp_n^3} \right)^N$$
What about $^4\text{He}$?

- First measurement of $^4\text{He}$ by the STAR collaboration in Au-Au collision at $\sqrt{s} = 200$ GeV/n

- $^4\text{He}/^3\text{He} \simeq 10^{-3}$

*STAR Collaboration, Nature 473 (2011)*
Secondaries cannot explain $^4\text{He}$

- The coalescence scenario predicts a hierarchy in the flux of anti-nuclei $\phi_{A+1} \approx 10^{-3} - 10^{-4} \phi_A$.
- AMS measurement is ~ 6 orders of magnitude above $^4\text{He}$ “secondary” prediction.
- Where is the anti-De???
All (recent) predictions agree!

- Blum++ 2017: AMS (5yrs) could detect ~1 or 2 events \( \text{if } B_3 = 10 \cdot B_3 \text{ from Alice!} \) AMS has detected ~6 events. probability -> 0.

- Korsmeier++ 2017: ~1-2 orders of magnitude below measurement.

- Same conclusions in Cirelli++ 2014, Herms++2016 etc…
What about Dark Matter?

The Dark Matter explanation suffers from very similar issues! Anti-He produced via coalescence of anti-proton and anti-neutron.

\[
q_{DM}(E_\bar{D}, \bar{x}) = \frac{1}{2} \left( \frac{\rho(\bar{x})}{m_{DM}} \right)^2 \langle \sigma v \rangle_{b\bar{b}} \frac{dN_{\bar{D}}}{dE_\bar{D}}
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\]

Coalescence factor can change: very different kinematic + non-nuclear material. It leads to typically smaller values of \(B_A\).
Dark Matter is at odds with AMS-02 events

Coogan&Profumo, PRD96 (2017) Korsmeier++ 1711.08465

- The Dark Matter flux peaks at low kinetic energy compared to the background.
- AMS should see associated $\overline{D}e$ and $\overline{p}$: Most of the parameter space is ruled out by $\overline{p}$.
- Dark Matter models cannot produce $^{4}\text{He}$ via coalescence.
Anti-helium as a probe of an anti-world

“[...] any observation of antihelium or even heavier antinuclei in space would indicate the existence of a large amount of antimatter elsewhere in the universe.”


“Production of anti-helium or heavier anti-nuclei in the interaction of ordinary matter in space is totally negligible; therefore observation of single anti-helium in space would constitute a strong argument in favor of such anti-matter domains.”

A. Kounine, proceedings of the ICRC 2011
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- Theoretically, anti-objects could be in a diffuse form (e.g. anti-clouds) or in a compact form (e.g. anti-stars).
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- Questions: i) How can such objects be produced?  
  ii) Can such objects survive over cosmological timescale?  
  iii) How can such objects accelerate CRs?  
  iv) How many of these objects do we need to explain the measurements?

  e.g. Dolgov&Silk 1993, Bambi&Dolgov 2007, Dolgov++ 0806.2986, Dolgov++ 1309.2746, Blinnikov++ 1409.5736
Anti-matter in the universe

From BBN and CMB we know

\[ \beta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \cdot 10^{-10} \]
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Where does the observed baryon asymmetry comes from?
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Where does the observed baryon asymmetry comes from?

- Three types of cosmological baryon asymmetry:
  i) \( \beta \) is homogeneous, the universe is 100% matter dominated;
  ii) average \( \beta \) is 0 but there are very large domains of matter and anti-matter;
  iii) \( \beta \) is not spatially constant: there are lumps of antimatter in a matter dominated universe.

  e.g. Bambi&Dolgov 2007

Given the large anti-matter flux measured by AMS-02 in our galaxy, we focus on scenario iii)
Anti-cloud cannot survive in our Galaxy

$\bar{p}$ can annihilate with $p$ in the ISM at a rate: $\tau^{-1}_{\text{ann}} = (n_p \langle \sigma_{pp} v \rangle)$

Our Galaxy exists since roughly $t_{\text{gal}} \simeq 2.8 \times 10^{17}$ s.

Plug in the annihilation cross-section $\Rightarrow n_p < 6.1 \times 10^{-5}$ cm$^{-3}$. 
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Anti-clouds cannot survive unless there is a segregation between matter and anti-matter.
Anisotropic BBN and the isotopic ratio

- Standard BBN predicts in the ISM: $\frac{^4\text{He}}{^3\text{He}} \sim 10^4$. Within CRs, spallation leads to $\frac{^4\text{He}}{^3\text{He}} \sim 5$. 
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Correct isotopic ratio if anti-$\eta = 10^{-3} \eta$.
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Anti-stars in the galaxy?

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- Primordial anti-stars could form from very dense clumps in anti-matter dominated region. It requires strong iso-curvature perturbations at small scales: almost no constraints!

- Idea similar to the formation of primordial black holes, already suggested over 25 years ago! Dolgov & Silk 1993
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- How many of them? What mass & composition? What is the acceleration mechanism?
High-energy cosmic rays from anti-stars

Even if such objects were created in the early universe, it is unclear how they can lead to high-energy cosmic rays.

Do they lead to supernovae explosion that accelerate the surrounding medium? Do they experience solar flares? Could there be thermo-nuclear explosions from annihilations at the surface?
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Parametrically we can estimate that from a single event occurring at a given time:

$$\Phi_{\text{He}} = \left( \frac{c}{V_{\text{gal}}} \right) \left( \frac{f_{\text{He}} M_\odot}{m_{\text{He}}} \right) f_{\text{acc}} = 10^{-9} \left( \frac{(4\pi/3)(10 \text{ kpc})^3}{V_{\text{gal}}} \right) \left( \frac{M_\odot}{M_\odot} \right) \left( \frac{f_{\text{acc}}}{10^{-8}} \right) \left( \frac{f_{\text{He}}}{1} \right) \text{He cm}^{-2}\text{s}^{-1}$$
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Helium would escape the galaxy in \(10^8\) yrs \(\sim 10^{-3}t_{gal}\): there might be a population of stars!
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Conclusions

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Alternatively, primordial anti-stars could be formed in the early universe from strong iso-curvature perturbations at small scales.

Depending on the (unknown) acceleration mechanism, it is conceivable that a single near-by anti-star contributes to the AMS-02 observation.
Back-up
Survival rate in the Early Universe

- In many scenarios, anti-regions will be produced in the early universe. The same calculation can be performed at that epoch.

- The hubble time before matter-radiation equality \((z_{eq} > 3500)\) is

\[
t_H \approx 5 \times 10^{19}(1 + z)^{-2} \text{ s}
\]

- Before BBN \((z > 10^6)\), annihilation happens in the relativistic regime. The constraint on the local proton density from requiring \(t_{\text{ann}} > t_H\) is:

\[
\frac{n_p^{\text{local}}(z > z_{BBN})}{n_p^{\text{cosmo}}(z_{BBN})} < \left( \frac{67}{1 + z} \right) \Rightarrow n_p^{\text{local}}(z_{BBN}) < 1.9 \times 10^{-8} n_p^{\text{cosmo}}(z_{BBN})
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If anti-domains were formed before BBN, there must be less than 1 baryon per \(10^8\) anti-baryons within them!
Clouds of anti-matter in our galaxy?

- Anti-clouds in our galaxy could explain AMS-02 events.
- How many of them? What are their densities? What volume would they occupy?
- AMS-02 measurements can help us answer these questions.
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- Measured by AMS-02: $10^{-8}$
- what we want to learn

- Are there small, very dense objects or large, very dilute anti-domains?
Some implications of the BBN calculation

- This immediately predicts density ratio:
  \[
  \frac{N(^{4}\text{He})}{N(^{3}\text{He})} \simeq 0.3 \Rightarrow \frac{N(\bar{p})}{N(^{3}\text{He})} \simeq 10^5
  \]

- We predict \(~10^4\) primary anti-proton and \(~0.1\) De event.

This is potentially detectable with AMS-02!
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- Question: can such objects survive in our galaxy? can we see them in \(\gamma\)-rays?
\section*{$\gamma$-Ray constraints}

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\textbf{\(\gamma\)-Ray constraints}

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- There are three types of searches that can provide strong constraints:

  i) searches for distinctive spectral features such as a gamma-ray line;

  ii) searches for morphological features localized on the sky, either from extended or point sources;

  iii) searches for a continuous spectrum of gamma-rays extending over large area on the sky (e.g. extragalactic \(\gamma\)-ray background).
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Type i) and iii) can provide very strong constraints on the overlap of matter/anti-matter region. Type ii) could explain some unassociated sources in the 3FGL catalog.
Constraints from a $\gamma$-ray line

- $\gamma$-ray constraints can be much stronger than the survival rate. Let’s see for instance the case of a line from $p\bar{p} \rightarrow \pi^0\gamma, \eta\gamma, \omega\gamma, \eta'\gamma, \phi\gamma, \gamma\gamma$.

Ackermann++ 1506.00013
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What could be wrong? (1)

- The coalescence scenario could be wrong:
  - Using the anti-De measurements we can predict what the anti-3He coalescence factor should be: very good agreement with what is measured by ALICE

\[
p_{\text{De}}^{\text{coal}} \in [0.218, 0.262] \text{ GeV} \quad p_{\text{He}}^{\text{coal}} \in [0.208, 0.262] \text{ GeV}
\]

- We have assumed a constant coalescence factor: could there be resonances?

no resonances observed in Alice data nor in MonteCarlo
The measurements could be problematic:

- Sensitivity to anti-De is much worse than that to anti-${}^3$He: did we miss them?
- The mass of the anti-${}^4$He could have been mis-reconstructed.
- Of course, the sign could be wrong…
Anti-cloud cannot survive in our Galaxy

- Our Galaxy exists since roughly $t_{\text{gal}} \approx 2.8 \times 10^{17}$ s.

- Antiproton can annihilate with proton in the ISM at a rate:

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  \langle \sigma_{pp} v \rangle \simeq \begin{cases} 
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- Are anti-clouds cold ($T < 10^4$ K) or hot and ionized ($T > 10^{10}$)?

- Requiring $t_{\text{ann}} > t_{\text{gal}}$ leads to
  $$n_p^{\text{cold}} < 3.5 \times 10^{-8} \text{ cm}^{-3} \quad \quad n_p^{\text{hot}} < 6.1 \times 10^{-5} \text{ cm}^{-3}.$$
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- Anti-clouds cannot survive unless there is a segregation between matter and anti-matter.