Updated secondary anti-helium cosmic ray fluxes
A first estimate for $^{4}\text{He}$

Pierre Salati – LAPTh & Université Savoie Mont Blanc

Outline

1) Anti-helium et advocati diaboli
2) Anti-helium production and the coalescence factor
3) Cosmic ray anti-helium Galactic propagation
4) A word on dark matter

V. Poulin, P.S., I. Cholis, M. Kamionkowski & J. Silk

Antideuteron 2019 – University of California, Los Angeles – March 27, 2019
1) Anti-helium et advocati diaboli

- $^3\text{He}$ (6) and $^4\text{He}$ (2) candidates have been identified by AMS-02. The event rate is $\sim 1$ anti-helium in 100 million helium.

- Massive background simulations are carried out to evaluate significance. The probability of a background origin for $\text{He}$ events is very small.

- More data are needed. Number of collected $\text{He}$ events should increase, while probability of background origin should decrease.
Secondary cosmic-ray anti-helium

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

\[ \Phi_i(E_i, \mathbf{x}) \]

\[ q_{\text{sec}} \]

\[ q_{\text{acc}} \]

\{ p, \alpha \} \text{ primaries}

\text{Fusion of } \overline{p} \text{ & } \overline{n}

\text{Coalescence factor } B

\text{Solar modulation with } \phi_p^F \neq \phi_{\overline{p}}^F

Courtesy Antje Putze, TeVPA 2015
2) Anti-helium production and the coalescence factor

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

\[ 2\Delta = k_1 - k_2 \]
\[ ||\Delta|| \leq p_0 \]

coalescence momentum $p_0 = \frac{p_{\text{coal}}}{2}$

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

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

Coalescence factor $B_2$

\[ \frac{E_{\bar{d}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{d}}}{d^3K} = B_2 \left\{ \frac{E_{\bar{p}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{p}}}{d^3k_1} \right\} \left\{ \frac{E_{\bar{n}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{n}}}{d^3k_2} \right\} \]
2) Anti-helium production and the coalescence factor

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

\[
p \xrightarrow{2\Delta = k_1 - k_2} H
\]

\[
\|\Delta\| \leq p_0
\]

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

Production on anti-nuclei with mass \(A\)

\[
\frac{E_A}{\sigma_{\text{in}}} \frac{d^3\sigma_A}{d^3k_A} = B_A \left\{ \frac{E_{\bar{p}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{p}}}{d^3k_{\bar{p}}} \right\}^Z \left\{ \frac{E_{\bar{n}}}{\sigma_{\text{in}}} \frac{d^3\sigma_{\bar{n}}}{d^3k_{\bar{n}}} \right\}^{A-Z} \text{ with } k_{\bar{p}} = k_{\bar{n}} = k_A/A
\]

Coalescence factor \(B_A\)

\[
B_A = \frac{m_A}{m_p m_n^{A-Z}} \left\{ \frac{\pi}{6} \frac{p_{\text{coal}}}{p_{\text{coal}}} \right\}^{A-1}
\]
Determination of the coalescence momentum

- No ab initio determination of $p_0$ which needs to be fitted to data. To do so, a model is required.

In Blum et al., $B_A \propto V^{1-A}$. The hadronic volume $V$ is probed by the HBT two-pion correlation measurements.

\[
\frac{B_2}{\text{GeV}^2} \approx 0.068 \left( \frac{R(p_t)}{1 \text{ fm}} \right)^2 + 2.6 \left( \frac{b_2}{3.2 \text{ fm}} \right)^2 \quad (12)
\]

\[
\frac{B_3}{\text{GeV}^4} \approx 0.0024 \left( \frac{R(p_t)}{1 \text{ fm}} \right)^2 + 0.8 \left( \frac{b_3}{1.75 \text{ fm}} \right)^2 \quad (11)
\]
Determination of the coalescence momentum

- Monte-Carlo event-generators are not devoid of problems. They are tuned to specific processes \( \neq \) antinucleon production. They yield different \( p_0 \) when adjusted to different data sets. \( p_0 \) depends on \( \sqrt{s} \).

![Fitting \( p_0 \) to data on \( \bar{d} \) production]

A. Ibarra & S. Wild, JCAP 1302 (2013) 021
Determination of the coalescence momentum

- Monte-Carlo event-generators are not devoid of problems. They are tuned to specific processes ≠ antinucleon production. They yield different $p_0$ when adjusted to different data sets. $p_0$ depends on $\sqrt{s}$.

---

Determinition of the coalescence momentum

- ALICE provides an experimental determination of $B_2$ and $B_3$. The $\bar{p}$ production cross-section is measured. Approximately the same value for $p_0$ from $\bar{d}$, $\bar{t}$ and $^3\text{He}$.

Determination of the coalescence momentum

- ALICE provides an **experimental** determination of $B_2$ and $B_3$. The $\bar{p}$ production cross-section is measured.

Approximately the same value for $p_0$ from $d$, $\bar{t}$ and $^3\text{He}$.

\[
208 \text{ MeV} \leq p_{\text{coal}} \leq 262 \text{ MeV}
\]

\[
218 \text{ MeV} \leq p_{\text{coal}} \leq 262 \text{ MeV}
\]

Local source term for anti-nuclei production in cosmic-rays

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


\[ 7.7 \times 10^{-7} \leq \frac{B_4}{\text{GeV}^6} \leq 3.9 \times 10^{-6} \]

\( \bar{p} \) production modeled as in
Local source term for anti-nuclei production in cosmic-rays

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

The STAR Collaboration, Nature 473 (2011) 353
3) Cosmic ray anti-helium Galactic propagation

\[\dot{\psi} + \nabla \cdot \{-K \nabla \psi + \psi \mathbf{V}_C\} + \frac{\partial}{\partial E} \left\{ b \psi - D_{EE} \frac{\partial \psi}{\partial E} \right\} = q - (\sigma \nu n_H) \psi\]

**convection**

**x diffusion**

\[K = K_0 \beta R^{\delta} \left\{ 1 + \left( \frac{R}{R_b} \right)^{\Delta \delta/s} \right\}^{-s}\]

**E diffusion**

\[D_{EE} = \frac{2}{9} \frac{V_A^2 \beta^4 E^2}{K}\]

(GeV/nuc)\(^{-1}\) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)

ISM spallation

\[q = q_{acc}, q_{sec}, q_{DM}\]
Positron constraints on cosmic ray propagation

\[ q_{\text{sec}}(e^+ | E_e, \mathbf{x}) = \sum_{i \in \{p, \alpha\}} \sum_{j \in \{H, He\}} 4\pi \int dE_i \ \Phi_i(E_i, \mathbf{x}) n_j(\mathbf{x}) \frac{d\sigma_{ij \rightarrow e^+}}{dE_e}(E_i, E_e) \]

\( e^+ \) diffuse and lose E

\( B/C \rightarrow K/L \) while \( e^+ \rightarrow K \)

Degeneracy between \( K \) and \( L \) can be lifted

Courtesy Antje Putze, TeVPA 2015
After skimming positron sphere alone, the measured range. It excludes the positron excess to be explained by DM particles. Significant improvements in modeling positron propagation have also been made. In particular, the so-called pinching method – a new trick – yields a decrease @ a few GeV to di-cutive pinching factor. Taking into account forces leads to effects leads to dependencies in the final fluxes below 10 GeV.

\[ \Phi_{e+}^{\text{sec}} \] forces \( K \) to be large \( \Rightarrow L \geq L_{\text{min}} \sim 8.5 \text{ kpc} \)

\[ \text{All B/C compatible CR models} \]

\[ \text{After skimming} \]

\[ \text{e}^+ \text{ excess above } \sim 1 \text{ GeV} \]

M. Boudaud et al., A&A 605 (2017) A17
Secondary anti-helium fluxes


AMS-02 should not have seen $^\text{He}$ events

no secondary origin $\Rightarrow$ DM or else
Secondary anti-helium fluxes

Determination of the coalescence momentum

- No ab initio determination of $p_0$ which needs to be fitted to data. To do so, a model is required.
- Monte-Carlo event-generators are not devoid of problems. They are tuned to specific processes ($=\text{anti-nucleon production}$). They yield different $p_0$ when adjusted to different data sets. $p_0$ depends on $p_s$.
- ALICE provides an experimental determination of $B_2$ and $B_3$. $\bar{p}$ production cross-section is measured.
- Approximately the same value for $p_0$ from $\bar{d}$, $\bar{t}$, and $\alpha$.

$208\text{ MeV} \leq p_{\text{coal}} \leq 262\text{ MeV}$


Local source term for anti-nuclei production in cosmic-rays

$\psi_{\text{sec}}(\text{He} | E_{\text{He}}, x) = \sum_i 2p_i \rho^i \times \sum_j 2H_{\text{He}} \rho^j \int dE_i(x) n_j(x) d\rho_{ij} \rho_{\text{He}}(E_i, E_{\text{He}})$

7. $7 \times 10^{-7} \leq B_4 \text{ GeV} \leq 3.9 \times 10^{-6}$


AMS-02 should not have seen $\bar{\text{He}}$ events

no secondary origin $\Rightarrow$ DM or else
4) A word on dark matter

Could anti-helium ($^3\bar{\text{He}}$) events be produced by DM?

- If AMS-02 $\bar{\text{He}}$ events are from DM, beware of $\bar{p}$ flux.
- To evade the $\bar{p}$ constraint, $p_{\text{coal}}$ exceedingly large.


4) A word on dark matter

Could anti-helium ($^3\bar{\text{He}}$) events be produced by DM?


- If AMS-02 $\bar{\text{He}}$ events are from DM, beware of $\bar{p}$ flux.
- To evade the $\bar{p}$ constraint, $p_{\text{coal}}$ exceedingly large.

MIN is excluded by positrons

Concluding remarks

• Anti-helium-3 and anti-helium-4 candidates have been identified by AMS-02. Massive background simulations are carried out to evaluate significance. More data are needed.

• \(^{3}\overline{\text{He}}\) events
  AMS-02 should not see secondary CR \(^{3}\overline{\text{He}}\).
  If \(^{3}\overline{\text{He}}\) events are produced by DM, a large \(\overline{p}\) excess is expected.
  Apart from a possible anomaly, no such excess is seen.

• \(^{4}\overline{\text{He}}\) events
  There is absolutely no hope to detect a single event.

If confirmed, a single \(^{4}\overline{\text{He}}\) would be a major discovery.
Concluding remarks

- Anti-helium-3 and anti-helium-4 candidates have been identified by AMS-02. Massive background simulations are carried out to evaluate significance. More data are needed.

- $^3\text{He}$ events
  AMS-02 should not see secondary CR $^3\text{He}$. If $^3\text{He}$ events are produced by DM, a large $\bar{p}$ excess is expected. Apart from a possible anomaly, no such excess is seen.

- $^4\text{He}$ events
  There is absolutely no hope to detect a single event. If confirmed, a single $^4\text{He}$ would be a major discovery.

Thanks for your attention