A Study of Astrophysical Backgrounds of Antihelium Nuclei in Cosmic Rays

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2nd Cosmic-ray Antideuteron Workshop at UCLA, March 27-29, 2019
Antinuclei in CR

Models have suggested antideuteron flux from dark matter (DM) annihilation could have orders of magnitude lower astrophysical background below $\sim 1$ GeV per nucleon.

Makes $\bar{d}$ and larger antinuclei interesting probes for DM.

**Figure:** Predicted $\bar{d}$ flux from Korsmeier et al. (PR D97, 103011)
AMS-02 and Antiheliums

AMS-02 measures cosmic ray particles with high precision. Reported antihelium candidates (six $^3\overline{He}$ and two $^4\overline{He}$)

Alberto Oliva presented on antinuclei on behalf of AMS-02

This leads to new challenges and questions about the production mechanisms of light nuclei, possible backgrounds from astrophysical sources and their propagation.
Antinucleons from DM annihilation can coalesce to form $\bar{d}$ or larger antinuclei (signal to search for)

Astrophysical background: produced in interactions of CR (mostly protons) and interstellar medium (ISM - mostly hydrogen)

Coalescence production of antinuclei with mass number $A$ and charge number $Z$ from collision of CR species $i$ with ISM species $j$:

$$
\frac{E_A}{\sigma_{ij}} \frac{d^3\sigma_A}{dk_A^3} = B_A \left( \frac{E_{\bar{p}}}{\sigma_{ij}} \frac{d^3\sigma_{\bar{p}}}{dk_{\bar{p}}^3} \right)^Z \left( \frac{E_{\bar{n}}}{\sigma_{ij}} \frac{d^3\sigma_{\bar{n}}}{dk_{\bar{n}}^3} \right)^{A-Z}
$$

where parameter $B_A \propto (p_0^3)^{A-1}$; (for $\bar{d}$, parameter $B_2 \propto p_0^3$)
Coalescence Parameter

- Two antinucleons coalesce to form antideuterons if in their CM frame:
  \[ \Delta k = \frac{1}{2} |\vec{k}_p - \vec{k}_n| < p_0 \]

- Coalescence momentum \( p_0 \) for \( \bar{d} \) formation is energy dependent (see Diego Gomez’s talk)
  \[ p_0(T) = \frac{A}{1 + \exp(B - \frac{\ln(T)}{C})} \]

- For EPOS-LHC:
  \[ A = 89.6 \text{ MeV/c}, \]
  \[ B = 6.6, \ C = 0.73, \ T \text{ is kinetic energy in GeV} \]

**Figure:** Energy dependence of \( p_0 \) for \( \bar{d} \) formation (PR D98, 023012)
Extension to Formation of Larger Antinuclei

All at the same time:

In an iterated process:

- For $^3\bar{He}$, one can consider coalescence of all three antinucleons together (each antinucleon pair satisfies condition)
- Or coalescence of two antinucleons and the coalescence of the product with a third
- Or a combination of both (for $^3\bar{He}$, parameter $B_3 \propto p_0^6$)
CR energies were selected (20, 50, 158, 500 and 2000 GeV) to probe variation of $p_0$ with collision energy $T$

EPOS-LHC was used to simulate 50 billion $p + p$ collisions

Afterburner script generated $\bar{d}$, $\bar{t}$ and $\bar{He}^3$ applying coalescence conditions to antinucleons (assuming all $\bar{t}$ decayed into $^3\bar{He}$, they were combined later)
Particle production rates from EPOS+coalescence afterburner

- 50 billion MC events generated, 50 $\bar{^3}\text{He}$ produced, 90 $\bar{t}$ produced
- Afterburner applied for $\bar{^4}\text{He}$ too, not enough statistics
- Orders of magnitude more $\bar{d}$ expected from same mechanism
We thank Vivian and Pierre for allowing us to use their propagation code.

Simulation is a computationally intensive process, limiting us to sampling CR energy, producing antinuclei statistics not enough for detailed propagation schemes.

Available $^3\overline{He}$ cross-section spectra from $p + p$ were scaled using the ratio of $p_0$'s used in the two studies (by comparing more numerous $\overline{d}$ spectra).

Local source terms propagated to predict expected $^3\overline{He}$ top-of-atmosphere flux.
The differences with other analytical studies possibly arise from the differences in the $p_0$ used in coalescence.
Differences of secondary production at low energies are magnified in effect by the steeply falling cosmic ray flux as a function of energy.
Conclusion

- With an event-by-event application of coalescence, we were able to look at production rates of rare antinuclei like antitritium, antihelium3
- This study specifically looks at the effect of the rising value of coalescence parameter with energy for antinuclei production
- We find that expected top-of-atmosphere flux of secondary antiheliums may be even smaller that previously expected
- This study motivates one to look for other (more exotic) sources of antinuclei in the cosmic rays
Outlook

- We aim to continue and extend the study to possibly:
  - sample more cosmic ray energies
  - look more carefully at methods of combining more than two nucleons
  - gather more statistic for smoother spectra of rare antinuclei
  - generate enough MC events to produce $^4\overline{He}$
Thank You
Backup
Inconclusive Light Antiparticles

- Models (pulsars, SNR acceleration) have been suggested to explain the positron excess
- Antiproton excess is within uncertainty range
- Clearer signal is needed for DM (indirect) detection

Figure: Ratio of positron to total (above) and $\bar{p}$ to $p$ (below)
Coalescence Parameter for Deuterons

Energy dependent coalescence parameter $p_0$ for deuteron formation
Local Source Term

\[ Q_{\text{sec}}^{ij}(E_A) = 4\pi n_j \int_{E_{\text{th}}}^{\infty} dE_i \phi_i(E_i) \frac{d\sigma_A^{ij}}{dE_A}(E_i, E_A) \]

Calculation of local source term
Sample Scaled $^3\bar{He}$ Spectra

CR $T_p = 5.01\times10^2$ GeV

$^3\bar{He}$ scaled using $p_0$ ratio from $\bar{d}$ spectra