A Study of Astrophysical Backgrounds of Antihelium Nuclei in Cosmic Rays

Amaresh Datta, Anirvan Shukla, Carina Kanitz, Philip Doetinchem

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 ~ 1 GeV per nucleon

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

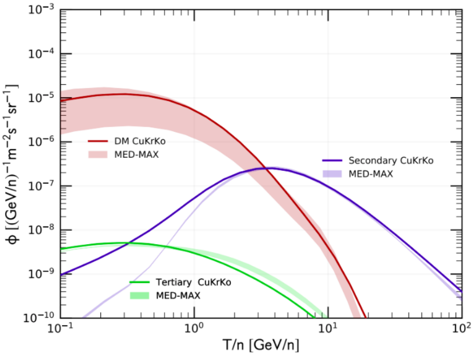
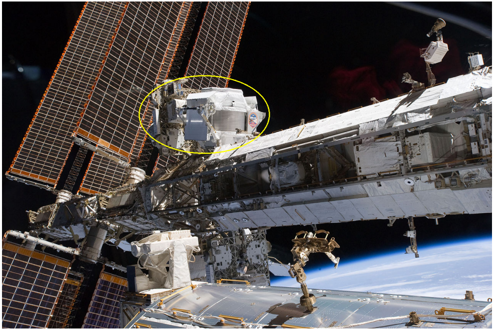


Figure: Predicted $\bar{d}$ flux from Korsmeier et al. (PR D97, 103011)

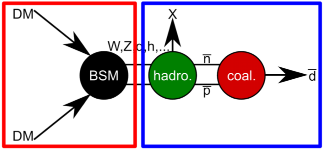
AMS-02 and Antiheliums



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

Coalescence Formation



- 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 :

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

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 :

$$\Delta k = \frac{1}{2}\left|\vec{k}_{\bar{p}} - \vec{k}_{\bar{n}}\right| < p_0$$

- 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 : $A = 89.6$ MeV/c, $B = 6.6$, $C = 0.73$, T is kinetic energy in GeV

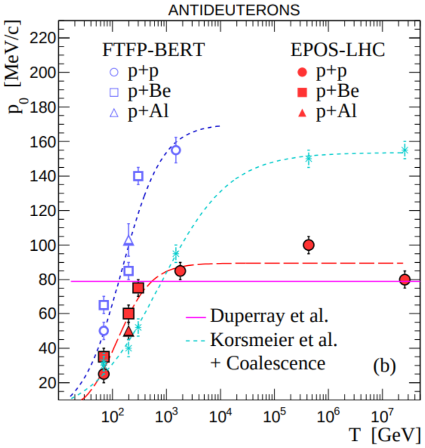
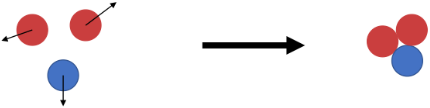


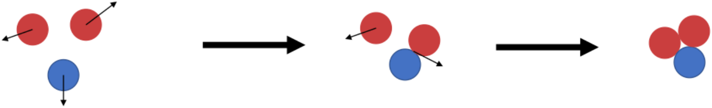
Figure: Energy dependence of p_0 for $\bar{d}$ formation (PR D98, 023012)

Extension to Formation of Larger Antinuclei

All at the same time:

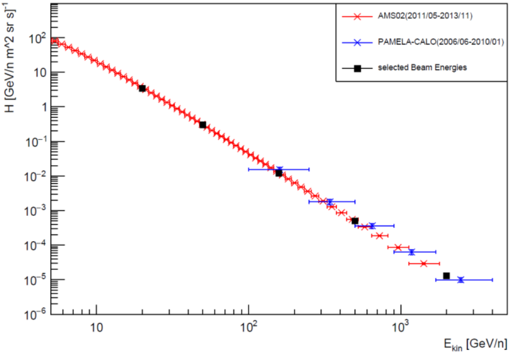


In an iterated process:



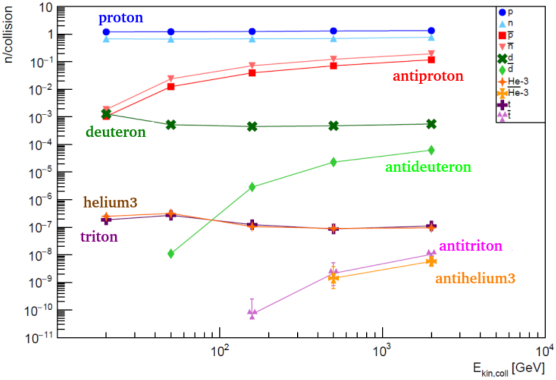
- For ${}^3\bar{He}$, one can consider coalescence of all three antinucleons together (each antinucleon pair satisfies condition)
- Or coalescence of two antinucleons and the coalescence of the product with a third
- Or a combination of both (for ${}^3\bar{He}$, parameter $B_3 \propto p_0^6$)

Simulation Steps



- 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)

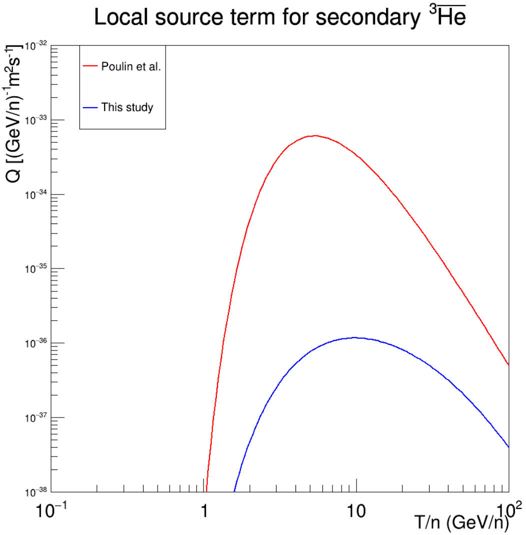
Production Rate



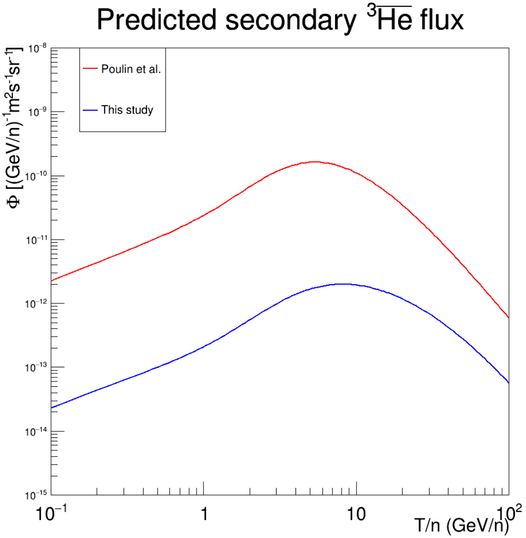
- Particle production rates from EPOS+coalescence afterburner
- 50 billion MC events generated, 50 $\bar{He}^3$ produced, 90 $\bar{t}$ produced
- Afterburner applied for $\bar{He}^4$ too, not enough statistics
- Orders of magnitude more $\bar{d}$ expected form same mechanism

Propagation

- We thank Vivian and Pierre for allowing us to use their propagation code
- Simulation is computation resource intensive process, limiting us to sample CR energy, produced antinuclei statistics not enough for detailed propagation schemes
- Available $^3\bar{He}$ cross-section spectra from $p + p$ was scaled using the ratio of p_0's used in the two studies (by comparing more numerous $\bar{d}$ spectra)
- Local source terms propagated to predict expected $^3\bar{He}$ top-of-atmosphere flux



The differences with other analytical studies possibly arise from the differences in the p_0 used in colescence



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 $^{4}\bar{He}$

Thank You

Backup

Inconclusive Light Antiparticles

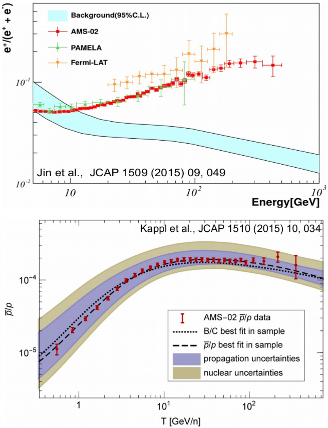
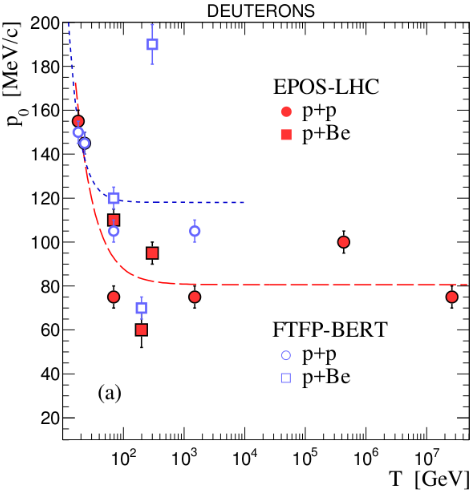


Figure: Ratio of positron to total (above) and $\bar{p}$ to p (below)

- 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

Coalescence Parameter for Deuterons



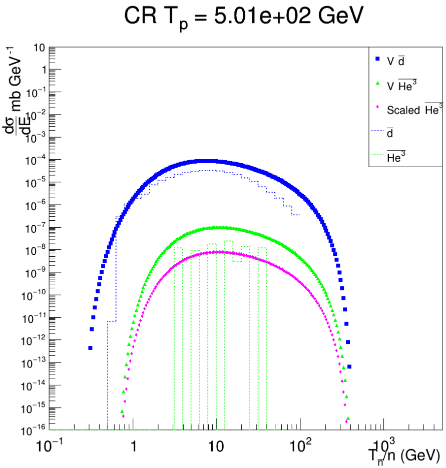
Energy dependent coalescence parameter p_0 for deuteron formation

Local Source Term

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

Calculation of local source term

Sample Scaled $^3\bar{He}$ Spectra



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