From accelerator measurements to particle astrophysics results

Philip von Doetinchem

philipvd@hawaii.edu
Department of Physics & Astronomy
University of Hawai'i at Manoa
http://www.phys.hawaii.edu/~philipvd
Cosmic rays as messengers

- modulation by solar wind
- deflection in magnetic field
- scattering in magnetic fields, interaction with interstellar medium
- interactions with atmosphere

AMS-02 status

proton $> 10\text{MeV}$ red
electron $> 10\text{MeV}$ green
positron $> 10\text{MeV}$ blue
neutron $> 10\text{MeV}$ turquoise
muon $> 10\text{MeV}$ magenta
photon $> 10\text{keV}$ yellow

20GeV proton

Doetinchem  Accelerator to Particle Astrophys  Jun 2022 - p.2
Dark matter signal in cosmic rays?

- unexplained feature in positrons:
  - astrophysical origin → pulsars
  - SNR acceleration
  - dark matter annihilation
- combined fit with antiproton and diffuse gamma-rays from the Galactic Center → 80GeV DM particle?
- understanding astrophysical background is a challenge better constraints on cosmic-ray propagation and astrophysical production are needed
Antideuterons as a probe of dark matter

- Antideuterons sensitive to a wide range of dark matter models, e.g.:
  - Generic 70GeV WIMP annihilation model that explains antiproton excess and $\gamma$-rays from Galactic center
  - Dark matter gravitino decay
  - Extra dimensions
  - Dark photons
  - Heavy DM models with Sommerfeld enhancement
  - Primordial black holes (antiprotons)

Antideuterons are an important unexplored indirect detection technique!
Cosmic-ray antihelium

- AMS-02 reported that several $\text{He}$ candidate events have been observed → interpretations are actively ongoing.

- Antiproton and antihelium both constrain antideuterons → no explanation of antihelium should overproduce antiprotons and antideuterons.

- Possible antihelium candidate explanations include:
  - Secondary astrophysical background
  - Dark matter annihilation or decay
  - Nearby antistar: at distance of ~1pc

Finding low-energy antihelium would be truly revolutionary new physics
**Uncertainties**

- **Cosmic-ray propagation:**
  - Important constraint for antinuclei flux from dark matter annihilations is the Galactic halo size, which directly scales the observable flux.
  - Fits of cosmic-ray nuclei data are very important to constrain cosmic-ray propagation models (e.g., Li/C, Li/O, Be/C, Be/O, B/C, B/O).
  - Inelastic interactions of antinuclei in the Galaxy.

- **Antinuclei formation** process breaks the degeneracy of antinuclei with antiprotons. Different approaches exist:
  - Coalescence: $\bar{d}$ can be formed by an $\bar{p}\bar{n}$ pair if relative momentum is small compared to coalescence momentum $p_0$.
  - Wigner-function based, semi-classical model has been developed (M. Kachelrieß et al., Eur. Phys. J. A 56, 4 (2020)).
  - Thermal model: Antinuclei directly formed at hadronization stage.

- Measurements of relevant primary cosmic ray and interstellar medium cross sections are important.
(Anti)deuteron formation: coalescence

- $\bar{d}$ can be formed by an $\bar{p}-\bar{n}$ pair if coalescence momentum $p_0$ is small

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

- use an event-by-event coalescence approach with hadronic generators
Coalescence modeling


- find $p_0$ for each data set where antiproton and antideuteron results exist
- $p_0$ show strong energy dependence in the range most important for cosmic rays
- more high-statistics data needed to constrain antinuclei formation models
Propagation equation:

\[ \frac{\partial \psi}{\partial t} = Q(r, p) + \text{div}(D_{xx} \text{grad} \psi - V \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \psi - \frac{\partial}{\partial p} \left[ \psi \frac{dp}{dt} - \frac{p}{3} (\text{div} \cdot V) \psi \right] - \frac{\psi}{\tau}, \]

- $D_{xx}$, $V$, and $D_{pp}$ are the spatial diffusion coefficient, the convection velocity, and the diffusive re-acceleration coefficient, respectively.
- $\psi/\tau$ accounts for particles lost via decay, fragmentation and inelastic interactions in the Galaxy.
Antihelium coalescence

- expanded modified MC coalescence model to merging multiple antinucleons from p-p interactions
  → requires quite a bit of computing power (~5,000 years, every additional antinucleon is about a factor of 1,000 suppressed → thanks UH HPC, OSG)
- use the $p_0$ behavior from antideuterons
- Very good agreement with ALICE antihelium-3 data (p-p at $\sqrt{s}=7$TeV)

A. Shukla et al. Phys Rev D 102, 063004 (2020)
Issues of the coalescence model

• **phase space** for ion production depends on the available energy in the formation interaction

• highly sensitive to **two-particle correlations** between the participating (anti)nucleons

• (anti)neutron spectra are challenging to access experimentally, potential asymmetries should be evaluated

• hadronic generators failing to describe (anti)proton and (anti)neutron spectra automatically result in a shift of $p_0$

• **spin** is not considered

• not a QM model

• generators not really tuned for antiparticle production → use dedicated antiproton, deuteron, and antideuteron data
Example for needed measurements

Predicted production of nucleons

- Deuterons
- Antideuterons

Tune hadronic generators with more information on nucleon correlations

Angular correlation of p-p pairs within a radius of $\Delta p=100\text{MeV}/c$
Future measurements

● NA61/SHINE at CERN SPS:
  ● Fixed target experiment
  ● High statistics $\bar{p}$ studies → Shukla: Identified hadron spectra in high-statistics $p+p$ collisions at 158 GeV/c (POS-OTH-02)
  ● C-$p$ fragmentation cross section measurements
  ● Deuteron production cross section, $d/p$ ratio
  ● Antiparticle correlation studies

● LHCb at LHC:
  ● Antideuteron production in heavy hadron decays and in fixed-target collisions
  ● Antihelium-3 from antilambda-b decays

● ALICE at LHC
  ● Antinuclei production
  ● Antinuclei inelastic cross sections

● AMBER at CERN SPS (upgraded COMPASS):
  ● Fixed target experiment
  ● High-statistics antiproton production cross section measurements
Summary

● Ideal range for relevant cosmic-ray antinuclei cross section studies is $p_{lab}=100\text{-}500\text{GeV/c}$ for $pp$

● Nuclei production measurements from various experiments and at a broad range of energies are already used

● Antiproton cross section uncertainties in the energy range of AMS-02 are at the level of 10–20%, with higher uncertainties for lower energies

● Full QM model for antinuclei formation needs to be further developed and validated

● More measurements are upcoming by many different experiments

● Reviews: Doetinchem et al., JCAP08 035 (2020), Snowmass21: arXiv 2201.00925

(Additional measurements needed for understanding of primary cosmic rays and positrons)