Light nuclei production in heavy ion collisions

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Light nuclei and anti-nuclei

Deuteron (d)  
\[ \text{p} \quad \text{n} \]

Tritium (t)  
\[ \text{p} \quad \text{n} \quad \Lambda \]

Helium-3 (\(^3\)He)  
\[ \text{p} \quad \text{p} \quad \text{n} \]

Hypertriton (\(^3\)\(\Lambda\))  
\[ \text{p} \quad \text{n} \quad \Lambda \]

Deuteron (\(\bar{d}\))  
\[ \overline{\text{p}} \quad \overline{\text{n}} \]

Tritium (\(\bar{t}\))  
\[ \overline{\text{p}} \quad \overline{\text{n}} \quad \Lambda \]

Helium-3 (\(\bar{3}\)\(\bar{\text{He}}\))  
\[ \overline{\text{p}} \quad \overline{\text{p}} \quad \overline{\text{n}} \]

Hypertriton (\(\bar{3}\)\(\bar{\Lambda}\))  
\[ \overline{\text{p}} \quad \overline{\text{n}} \quad \overline{\Lambda} \]

These and other nuclei are created in heavy ion collisions.
Anti-helium by Alpha-Magnetic Spectrometer

- Few events (compatible with) $^3\text{He}$, $^4\text{He}$
  Caveats: hard measurement, 1 event/year, not published
- Where do they come from?
  Antimatter clouds? Dark matter annihilations? pp collisions?
Understanding anti-helium measurement by AMS


  Conclusion: $\overline{\text{He}}$ production compatible with $pp$

  Use coalescence model for $pp \rightarrow \overline{\text{He}} + X$

- V. Poulin, P. Salati, I. Cholis, M. Kamionkowski and J. Silk, "Where do the AMS-02 antihelium events come from?", PRD 99, no. 2, 023016 (2019)

  Conclusion: $pp$ cannot produce that much $\overline{\text{He}}$

  advocate presence of anti-clouds in our Galaxy

  Use coalescence model for $pp \rightarrow \overline{\text{He}} + X$

Both use $pp$ collisions data from ALICE to calibrate models

Extrapolation from $pp \rightarrow \tilde{d}$ to $pp \rightarrow \overline{\text{He}} + X$, $pA \rightarrow \overline{\text{He}} + X$, $AA \rightarrow \overline{\text{He}} + X$, from high to low energies, from midrapidity to forward rapidity involved
Light nuclei and critical fluctuations

Generic critical point feature: **spatial** fluctuations increase
Nucleon density fluctuations in coordinate space


Proton and neutron density:

\[ \rho_n(x) = \langle \rho_n \rangle + \delta \rho_n(x) \]
\[ \rho_p(x) = \langle \rho_p \rangle + \delta \rho_p(x) \]

From a simple coalescence model

\[ N_d \approx \frac{3}{2^{1/2}} \left( \frac{2\pi}{mT} \right)^{3/2} \int d^3x \rho_p(x)\rho_n(x) \sim \langle \rho_n \rangle N_p (1 + C_{np}) \]
\[ N_t \approx \frac{3^{1/2}}{4} \left( \frac{2\pi}{mT} \right)^3 \int d^3x \rho_p(x)\rho_n^2(x) \sim \langle \rho_n \rangle^2 N_p (1 + 2C_{np} + \Delta \rho_n) \]

\[ \frac{N_t N_p}{N_d^2} = \frac{1}{2\sqrt{3}} \frac{1 + 2C_{np} + \Delta \rho_n}{(1 + C_{np})^2} \]

Thermal ratio

\[ \frac{g_t g_p}{g_d^2} \left( \frac{3m \cdot m}{(2m)^2} \right)^{3/2} = \frac{1}{2\sqrt{3}} \approx 0.29 \]

Light nuclei are sensitive to spatial density fluctuations
Comparing the $p$-$d$-$t$ ratio to NA49, STAR, and ALICE data

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\[
\frac{N_t N_p / N_d^2}{1 + \text{Res} \rightarrow p} \approx \frac{1}{2\sqrt{3}}
\]
Comparing the $p-d-t$ ratio to NA49, STAR, and ALICE data

Models do not agree with each other and with the data. Are the bumps related to fluctuations?
Why do models disagree?

This disagreement is conceptual: different ideas about when, where, and how light nuclei are produced

Let us overview, test and understand:

*Coalescence models*

*Thermal model*

*Purely dynamical models*
Types of coalescence

Main principles:

- Nuclei are formed at late stages of collision
- Nucleons bind into nuclei if they are close in phase space

Analytical coalescence

- Without nuclei wavefunction
  Csernai, Kapusta, Phys. Rept. 131 (1986) 223-318

- With nuclei wavefunction
  Sun, Chen, Phys.Rev. C95 (2017) no.4, 044905

Dynamical model + coalescence

- Transport + coalescence
  Zhu, Ko, Yin, PRC 92 (2015) no.6, 064911
  Dong et al., EPJ A 54 (2018) no.9, 144
  Liu et al., arXiv:1909.09304

- Hydro + coalescence
  Ivanov, Soldatov, EPJ A 53 (2017) no.11, 218

- Hybrid + coalescence

Disclaimer: References list is not comprehensive. Sorry.
Simple analytical coalescence framework

- Nucleons bind into nuclei if they are close in phase space

\[ E_A \frac{dN_A}{d^3P_A} = B_A \left( E_P \frac{dN_P}{d^3P_P} \right)^Z \left( E_n \frac{dN_n}{d^3P_n} \right)^N \Bigg|_{P_P=P_n=P_A/A} \]

- Expectations:
  - \( B_A \sim V_{HBT}^{-(A-1)}, \quad B_{A=2} \sim 1/V_{HBT}, \quad B_{A=3} \sim 1/V_{HBT}^2 \)
  - \( B_A(p_T) \) grows with \( p_T \) in AA, \( B_A(p_T) \approx \text{const} \) in pp
  - \( B_A \) decreases with larger multiplicity
  - \( \nu_2^d(2p_T) = 2\nu_2^p(p_T) \)

  Qualitatively these naive expectations are fulfilled.

- Attempts to get more precision:
  - More realistic proton phase space distribution from dynamical models
  - Advanced coalescence: account for nuclei wavefunction
Example of [hydro +] transport + coalescence

Recipe to make a deuteron:
1. Take nucleon pair at $t = \text{maximum of last interaction times}$
2. Boost to their rest frame
3. Bind $|\Delta p| < 0.28 \text{ GeV}$ and $|\Delta x| < 3.5 \text{ fm}$
4. Take isospin factor into account

Good description from low to high energies with 2 parameters
Advanced analytical coalescence


Prediction: large wavefunctions are suppressed

\[ N_A \sim \left( R^2 + \frac{r_A^2}{4} \right)^{-3/2} \]

\( R \) – size of the system

\( r_A \) – size of nucleus

Does wavefunction size matter? To be tested in small systems.
Wavefunction size: recalling AGS results

AGS, E864 experiment, central Au-Pb/Pt, 11.6 A GeV

\[ y = 1.9, \quad p_T / A = 200 \text{ MeV} \]

after correction for \( A, I_z \) and spin

Larger wavefunctions are suppressed, as advanced coalescence expects

Prediction: \( ^3_\Lambda \text{H} \) is big, it must be suppressed
Thermal + blast wave model vs. coalescence

Does wavefunction size matter?

Coalescence: yes, Thermal: no

Thermal: yields at $T = 156$ MeV, spectra — blast wave, $T \approx 115$ MeV

Advanced analytical coalescence:

$^3\Lambda$H is big, it must be suppressed

Data: $^3\Lambda$H disfavors coalescence

- Thermal production at higher energies and coalescence at lower?
- Maybe $^3\Lambda$H is born small?
Thermal model and “snowballs in hell” puzzle

• Nuclei formed early — at hadronic freeze-out
  \[ N_A \approx g_A V \left( \pi T m_A / 2 \right)^{3/2} e^{(A \mu_B - m_A) / T} \]
• ALICE fit of yields, Pb+Pb, \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \): \( T = 155 \text{ MeV} \)
• Nuclei momentum spectra: \( T_{kin} \approx 110 \text{ MeV} \)
• How can they survive from chemical to kinetic freeze-out?
• Binding energies: \( d, ^3\text{He}, ^3\Lambda\text{H}, ^4\text{He} \) – 2.2, 7.7, 0.13, 8.5 MeV

Snowballs in hell.
Purely dynamical model

- SMASH hadronic afterburner  J. Weil et al., PRC 94, no. 5, 054905 (2016)
- Treat deuteron as a single particle
  - implement deuteron + X cross-sections explicitly
Light nuclei production by pion catalysis

- $\pi d \leftrightarrow \pi np, \pi t \leftrightarrow \pi nnp, \pi^3 \text{He} \leftrightarrow \pi npp$
- all are tested to obey detailed balance within 1% precision
- large disintegration cross sections $\rightarrow$ large reverse rates

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907
$B_2(p_T)$ and $\nu_2$ for different centralities

$B_2(p_T) = \frac{1}{2\pi p_T dp_T dy} \left| \frac{d^3 N_d}{dp_T dp_T dy} \right|^{p_T=2p_T} \left( \frac{1}{2\pi p_T dp_T dy} \right)^2$

No free parameters. Works well for all centralities.
\(B_2(p_T)\) and \(v_2\) for different centralities

\[
B_2(p_T) = \frac{1}{2\pi} \left. \frac{d^3 N_d}{p_T dp_T dy} \right|_{p_T^d = 2p_T} \left( \frac{1}{2\pi} \frac{d^3 N_P}{p_T dp_T dy} \right)^2
\]

No free parameters. Works well for all centralities.
Does deuteron freeze out at 155 MeV?

Only less than 1% of final deuterons originate from hydrodynamics.

Deuteron freezes out at late time. Its chemical and kinetic freeze-outs roughly coincide.
Is $\pi d \leftrightarrow \pi np$ reaction equilibrated

After about 12-15 fm/c within 5% $\pi d \leftrightarrow \pi np$ is equilibrated
The yield is almost constant. Why? Does afterburner really play any role?
Deuteron yield

No deuterons at particlization: also possible. Here **all** deuterons are from afterburner.
Deuteron yield

No deuterons at particlization: also possible. Here all deuterons are from afterburner.
Why thermal model describes light nuclei yields at LHC

- Stable hadron yields ($\pi$, $K$, $N$, $\Lambda$, ...) comprising resonances are fixed at chemical freeze-out

- Nuclei are kept in partial (relative) equilibrium by huge cross-sections of $A + h \leftrightarrow A \times N + h$ until kinetic freeze-out
  - Therefore nuclei yields stay constant from hadron chemical freeze-out to kinetic
  - This picture works for all measured nuclei at LHC
    - Vovchenko et al, arXiv:1903.10024
  - It works even if no nuclei are produced at chemical freeze-out
    - DO, Pang, Elfner, Koch, MDPI Proc. 10 (2019) no.1, 6

- If wavefunction is large or very large – does not matter as long as the cross-sections are large enough to keep relative equilibrium
  - This might explain thermal $^3\text{He}$ and $^3\Lambda\text{H}$ at LHC
Exactly the same mechanism, lower energies


Still works for deuteron!

Note (unpublished) jump from 14 to 5 in deuteron yield at $\approx 4.6$ GeV.
Conclusions

We need better understanding of light nuclei production
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We need better understanding of light nuclei production

- Potential benefits
  - Estimation of background for antimatter in space from pp, pA, AA. May lead to discovery of antimatter clouds in the Universe
  - Possible detection of critical point from density fluctuations $\Rightarrow \frac{N_t N_p}{N_d}$
Conclusions

We need better understanding of light nuclei production

- Potential benefits
  - Estimation of background for antimatter in space from pp, pA, AA.
    May lead to discovery of antimatter clouds in the Universe
  - Possible detection of critical point from density fluctuations \( \Rightarrow \frac{N_t N_p}{N_d^2} \)

- Challenges
  - No present model can explain measured \( \frac{N_t N_p}{N_d^2} \left( \sqrt{S_{NN}} \right) \)
  - Need to improve models, both dynamical and analytical
  - Need models including critical point
  - Does wavefunction size matter? Sometimes yes, sometimes no...
    To be further tested in small systems
  - Need hadronic exclusive cross-sections: \( d + \pi, d + p, t + \pi, t + p, \ldots \)
    to be measured or analytically computed
Thank you!
Thank you!
Rapidity dependence from NA49

Central PbPb, $\sqrt{s_{NN}} = 6.3 - 17.3$ GeV, deuteron

Uncertainty at high rapidity: AMS needs $4\pi$ yields of $\overline{\text{He}}$
Helium-3: lines by SMASH (preliminary), circles by NA49

Rule of thumb: light nuclei are described as good/bad as protons
Naive coalescence framework

- Nuclei are formed at late stages of collision
- Nucleons bind into nuclei if they are close in phase space

\[ E_A \frac{dN_A}{d^3P_A} = B_A \left( E_p \frac{dN_p}{d^3P_p} \right)^Z \left( E_n \frac{dN_n}{d^3P_n} \right)^N \bigg|_{P_p=P_n=P_A/A} \]

- Expectations:
  - \( B_A \sim \left( \frac{4}{3} \pi p_0^3 \right)^{A-1} \) or \( B_A \sim V_{HBT}^{-(A-1)} \)
  - \( B_2 \sim 1/V_{HBT}, B_3 \sim 1/V_{HBT}^2 \)
  - \( B_A(p_T) \approx \text{const} \) in pp
  - larger charged multiplicity, smaller \( B_A \)
  - \( v_2^d(2p_T) = 2v_2^p(p_T) \)

Are these naive expectations fulfilled?
Dependencies of $B_2$: transverse momentum

compatible with coalescence expectation

$V_{HBT}(m_T) \downarrow$, $B_2(m_T) \uparrow$
Dependencies of $B_2$: transverse momentum


compatible with coalescence expectation $V_{HBT}(m_T)$
Dependencies of $B_2$: system size

M. Puccio, Quark Matter 2018 proceedings, NPA 982 (2019) 447-450

compatible with coalescence expectation

$V \uparrow$, $B_2 \downarrow$
Dependencies of $B_2$: collision energy

STAR, arXiv:1903.11778

Not really compatible with $B_A \sim V_{HBT}^{-(A-1)}$ qualitatively!
Dependencies of $B_2$: collision energy


But the order of magnitude is still right
Most important deuteron production/disintegration reactions

Largest d + X disintegration rate $\rightarrow$ largest reverse production rate

Most important = largest $\sigma_{d+X}^{\text{inel}} n_X$

| X     | $\sigma_{d+X}^{\text{inel}}$ [mb] ($\sqrt{s} - \sqrt{s_{\text{thr}}} = [0.05, 0.25]$ GeV) | $\frac{dN_X}{dy} \big|_{y=0}$ |
|-------|-----------------------------------------------------------------|--------------------------------|
| $\pi^\pm$ | 80 - 160 | 732 |
| $K^+$ | $< 40$ | 109 |
| $K^-$ | $< 80$ | 109 |
| $p$ | 50 - 100 | 33 |
| $\bar{p}$ | 80 - 200 | 33 |
| $\gamma$ | $< 0.1$ | comparable to $\pi$? |

$\pi + d$ are the most important because of pion abundance
Reactions of deuteron with pions

\[ \pi d \leftrightarrow \pi np \] is the most important at LHC energies

\[ \sigma_{\pi d}^{inel} > \sigma_{\pi d}^{el} \], not like for hadrons
Reactions of deuteron with (anti-)nucleons

$\sigma_{pd}^{tot} - \sigma_{pd}^{el}$

[Carlson et al]

$\sigma_{Nd\rightarrow Nnp}$

SMASH

$\sigma$ [mb]

$\sqrt{s}$ [GeV]

2.8 2.85 2.9 2.95 3 3.05 3.1

$Nd \leftrightarrow Nnp$, $\bar{N}d \leftrightarrow \bar{N}np$: large cross-sections

but not important at LHC energies, because $N$ and $\bar{N}$ are sparse
Reactions of deuteron with (anti-)nucleons

\[ \sigma_{pd} \text{ inelastic} \]

[Ref: Bizzarri et al]

\[ \sigma_{Nd\rightarrow Nnp} \]

SMASH

\[ \sqrt{s} \text{ [GeV]} \]

\[ \sigma \text{ [mb]} \]

\[ 350 \]

\[ 300 \]

\[ 250 \]

\[ 200 \]

\[ 150 \]

\[ 100 \]

\[ 50 \]

\[ 0 \]

\[ 2.8 \]

\[ 2.9 \]

\[ 3 \]

\[ 3.1 \]

\[ 3.2 \]

\[ Nd \leftrightarrow Nnp, \ \tilde{N}d \leftrightarrow \tilde{N}np: \text{ large cross-sections} \]

but not important at LHC energies, because \( N \) and \( \tilde{N} \) are sparse
Transverse momentum spectra

Pion and kaon spectra not affected by afterburner
Proton spectra: pion wind effect and $B\bar{B}$ annihilations ($\sim 10\%$)
Obtaining $B_2(p_T)$ coalescence parameter

$$B_2(p_T) = \frac{1}{2\pi} \left. \frac{d^2N_d}{p_T dp_T dy} \right|_{p_T=2p_T^0} \frac{1}{\left( \frac{1}{2\pi} \frac{d^2N_p}{p_T dp_T dy} \right)^2}$$

The graph shows the reproduction of $B^2$ without any free parameters.
$p_T$-spectra for different centralities

![Graph showing $p_T$-spectra for different centralities](image)

- 0-10% x4
- 10-20% x2
- 20-40%
- 40-60%
- 60-80%

Pb+Pb, 2.76 TeV

$1/N_e v 1/2 \pi p_T d^2 N/dp_T dy$ [GeV$^{-2}$]

$10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^0$

$p_T$ [GeV]
\( p_T \)-spectra for different centralities

Pb+Pb, 2.76 TeV

0-10% x8
10-20% x4
20-40% x2
40-60%
60-80%

\[ \frac{1}{N_{ev}} 1/2 \pi p_T d^2 N/dp_T dy \] [GeV^{-2}]

\[ 10^{-6} \]
Toy model of deuteron production: no annihilations

- only $\pi$, $N$, $\Delta$, and $d$
- isoentropic expansion
- pion number conservation
- baryon (not net!) number conservation

\[
(s_{\pi}(T, \mu_{\pi}) + s_N(T, \mu_B) + s_{\Delta}(T, \mu_B + \mu_{\pi}) + s_d(T, 2\mu_B))V = \text{const}
\]
\[
(\rho_{\Delta}(T, \mu_B + \mu_{\pi}) + \rho_{\pi}(T, \mu_{\pi}))V = \text{const}
\]
\[
(\rho_N(T, \mu_B) + \rho_{\Delta}(T, \mu_B + \mu_{\pi}) + 2\rho_d(T, 2\mu_B))V = \text{const}
\]
Toy model of deuteron production: results

No annihilation: deuteron yield grows, like in simulation.
Toy model of deuteron production: results

$T_{\text{particlization}} = 165 \text{ MeV}$. Relative yields are similar, like in simulation.
Toy model of deuteron production: results

Annihilation out of equilibrium: $\mu_B = \mu_B^a \frac{V}{V_0} + \mu_B^r$, $a = 0.1$ $T_{\text{particlization}} = 155$ MeV.
Toy model of deuteron production: results

Annihilation out of equilibrium: \( \mu_B = \mu_B \frac{V/V_0}{a+V/V_0}, \quad a = 0.1 \quad T_{\text{particlization}} = 165 \text{ MeV}. \)

Qualitatively similar to our simulation.