“Snowballs from hell”:
light nuclei production in heavy ion collisions

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June 12, 2019

Strangeness in Quark Matter 2019
Outline

- Light (anti-)nuclei: challenges
  
  *Snowballs from hell*
  *Light nuclei and critical fluctuations*
  *Antihelium from space*
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- Light (anti-)nuclei: challenges
  
  *Snowballs from hell*
  
  *Light nuclei and critical fluctuations*
  
  *Antihelium from space*

- Which models could address these challenges?
  
  How well do they work?
  
  *Naive coalescence (no account of wavefunction)*
  
  *Advanced coalescence (account of wavefunction)*
  
  *Dynamical models + coalescence*
  
  *Dynamical models (no coalescence)*
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  *Dynamical models + coalescence*
  *Dynamical models (no coalescence)*

• Possible solution of *Snowballs from hell* challenge
Challenge I: Snowballs from hell

- Nuclei yields in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV:
  \[ N_A = \frac{g_A V}{2\pi^2} T m_A^2 K_2(m_A/T), \quad T = 155 \text{ MeV} \]
- Nuclei spectra: $T_{kin} \simeq 110 \text{ MeV}$
- How can they survive from chemical to kinetic freeze-out?
- Binding energies: $d, ^3\text{He}, ^3\Lambda\text{H}, ^4\text{He} - 2.2, 7.7, 0.13, 8.5 \text{ MeV}$

Snowballs in hell.


Light nuclei: rapid chemical freeze-out at 155 MeV, like hadrons?
Challenge II: Light nuclei and critical fluctuations

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


Proton and neutron density:

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

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

Correlations and fluctuations:

\[ C_{np} \equiv \frac{\langle \delta \rho_n(x) \delta \rho_p(x) \rangle}{\langle \rho_n \rangle \langle \rho_p \rangle} \]

\[ \Delta \rho_n \equiv \frac{\langle \delta \rho_n(x)^2 \rangle}{\langle \rho_n^2 \rangle} \]

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 model expectation (with \( N_p \) – thermal protons)

Light nuclei are sensitive to spatial density fluctuations
Extracting fluctuations from NA49 data

\[ C_{np} \equiv \frac{\langle \delta \rho_n(x) \delta \rho_p(x) \rangle}{\langle \rho_n \rangle \langle \rho_p \rangle}, \quad \Delta \rho_n \equiv \frac{\langle (\delta \rho_n)^2 \rangle}{\langle \rho_n \rangle^2} \]

Central Pb+Pb collisions
(y=0)


data: NA49, Phys. Rev. C94 (2016) no.4, 044906

Are the bumps related to fluctuations?
Can one reproduce them without assuming critical point?
• 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

- K. Blum, K. C. Y. Ng, R. Sato and M. Takimoto,
  “Cosmic rays, antihelium, and an old navy spotlight,”, PRD 96, no. 10, 103021 (2017)

Conclusion: $\bar{\text{He}}$ production compatible with pp
Use coalescence model for $pp \rightarrow \bar{\text{He}} + X$

- 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 $\bar{\text{He}}$
advocate presence of anti-clouds in our Galaxy
Use coalescence model for $pp \rightarrow \bar{\text{He}} + X$

- Both use pp collisions data from ALICE to calibrate models
- Extrapolation from $pp \rightarrow \bar{d}$ to $pp \rightarrow \bar{\text{He}} + X$, $pA \rightarrow \bar{\text{He}} + X$, $AA \rightarrow \bar{\text{He}} + X$, from high to low energies, from midrapidity to forward rapidity involved
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 $\overline{\text{He}}$
Theoretical approaches to light nuclei production

- **Thermal model**
- **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
    - Dong et al., Eur.Phys.J. A54 (2018) no.9, 144
  - Hydro + coalescence
  - Hydro + transport + coalescence
- **Dynamical model, no coalescence**
  - Light nuclei as a single degree of freedom
  - Light nuclei bound by potentials

Disclaimer: References list is not comprehensive. Sorry.
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

STAR, arXiv:1903.11778

compatible with coalescence expectation

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


compatible with coalescence expectation

$V_{HB T}(m_T) \downarrow, B_2(m_T) \uparrow$
Dependencies of $B_2$: system size

compatible with coalescence expectation

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

Not really compatible with $B_A \sim V_{HBT}^{-(A-1)}$ qualitatively!

$V_{HBT} \downarrow \uparrow \quad \Rightarrow \quad$ naive coalescence: $B_A \uparrow \downarrow$
Dependences of $B_2$: collision energy

But the order of magnitude is still right
Elliptic flow of light nuclei

Good agreement with $v_2^A(Ap_T) = Av_2^D(p_T)$
Elliptic flow of light nuclei

Good agreement with $v_2^A(\Delta p_T) = A v_2^p(p_T)$
Advanced coalescence

Prediction: large wavefunctions are suppressed

\[ B_2 = \frac{3\pi^{3/2} \langle C_d \rangle}{m_T R_\perp^2 (m_T) R_\parallel (m_T)} \]

\[ \langle C_d \rangle = \frac{1}{\left[ 1 + \frac{r^2}{4R_\perp^2} \right] \left[ 1 + \frac{r^2}{4R_\parallel^2} \right]^{1/2}} \]

\[ B_A \sim \left( R^2 + \frac{r^2_A}{4} \right)^{-3/2} \]

Does wavefunction size matter? To be tested.
[Hydro +] transport + coalescence


- Take nucleon pair at $t = \text{max. of latest interaction times}$
- Boost to their rest frame
- Bind $|\Delta p| < 0.28$ GeV and $|\Delta x| < 3.5$ fm
- Take isospin factor into account

Good description from low to high energies with 2 parameters
[Hydro +] transport + coalescence


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Good description from low to high energies with 2 parameters
Challenge I: Snowballs from hell

- Assuming rapid freeze-out of nuclei together with hadrons
- Nuclei yields in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV:
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Snowballs in hell.


Light nuclei: rapid chemical freeze-out at 155 MeV, like hadrons?
Purely dynamical model
Oliinychenko, Pang, Elfner, Koch, MDPI

- 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
Reactions with deuteron implemented in SMASH

- $\pi d \leftrightarrow \pi np$, $\pi d \leftrightarrow np$, elastic $\pi d \leftrightarrow \pi d$
- $N d \leftrightarrow N np$, elastic $N d \leftrightarrow N d$
- $\bar{N} d \leftrightarrow \bar{N} np$, elastic $\bar{N} d \leftrightarrow \bar{N} d$
- CPT conjugates of all above – reactions for anti-deuteron
- all are tested to obey detailed balance within 1% precision

$\pi d \leftrightarrow \pi np$ is the most important at high (LHC) energies
$N d \leftrightarrow N np$ is the most important at low (AGS) energies
$B_2(p_T)$ and $\nu_2$ for different centralities

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

PbPb, $\sqrt{s} = 2.76$ TeV, deuterons

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

Only less than 1% of final deuterons original from hydrodynamics

![Graph showing deuteron freeze-out]

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

\[ \frac{dN}{dy} |_{\text{ALICE}} \times (\Delta y = 2) \]

PbPb, 0-10%, \( \sqrt{s} = 2.76 \) TeV, \(|y| < 1\)

deuteron x3 init
default d init
no deuteron init

deuteron multiplicity

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

Without $B\bar{B}$ annihilations yield coincidence is less impressive
Deuteron yield

PbPb, 0-10%, $\sqrt{s} = 2.76$ TeV, $|y| < 1$

deuteron x3 init
default d init
no deuteron init
w/o BB annihilation
Freeze-out at 165 MeV

dN/d$y$ | ALICE | $\times (\Delta y = 2)$

t [fm/c]

But it persists if $T$ of particlization is changed to 165 MeV
Why thermal model works for light nuclei

- Stable hadron yields ($\pi$, $K$, $N$, $\Lambda$, dots) including resonances are fixed at chemical freeze-out
- Each conserved hadron gets chemical potential
- 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
  Vovchenko et al, arXiv:1903.10024
- It works even if no nuclei are produced at chemical freeze-out
  Oliinychenko, Pang, Elfner, Koch, MDPI
- If wavefunction is large or very large – does not matter as long as the cross-sections are large enough to keep relative equilibrium
Conclusions

- Nuclei do not freeze out chemically with hadrons. But their yields are determined at chemical freeze-out. Because nuclei are bound to nucleons by partial equilibrium.
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- Advanced coalescence: does wavefunction size matter? To be tested.

- Dynamical models + coalescence: need them to understand the role of fluctuations on light nuclei. Thermal / blast wave does not help here. Correct underlying phase-space distribution of nucleons is important.

- Need more purely dynamical models studies. Need hadronic exclusive cross-sections: $d + \pi$, $d + p$, $t + \pi$, $t + p$, ... to be measured or analytically computed.
Conclusions

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Conclusions

- Nuclei do not freeze out chemically with hadrons. But their yields are determined at chemical freeze-out. Because nuclei are bound to nucleons by partial equilibrium.
- Advanced coalescence: does wavefunction size matter? To be tested.
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Thank you!
Selected experimental results: spectra

- **NA49** *Phys. Rev. C*94* (2016) no. 4, 044906
  - $\sqrt{s_{NN}} = 6.3 - 17.3$ GeV
  - central Pb+Pb collisions
  - $d$, $t$, $^3$He
  - $p_T$ and $y$ differential

- **STAR** *arXiv:1903.11778*
  - $\sqrt{s_{NN}} = 7.7 - 200$ GeV
  - 5 centrality classes Au+Au
  - $d$, $\bar{d}$
  - midrapidity, $p_T$ differential

- **ALICE** *Phys. Rev. C*93* (2016) no. 2, 024917
  - $\sqrt{s_{NN}} = 2.76$ TeV
  - 5 centrality classes Pb+Pb, pp
  - $d$, $^3$He, $^3\Lambda$H, $^4$He and anti-particles
  - midrapidity, $p_T$ differential
Flashing deuteron spectra

ALICE, PbPb @ $\sqrt{s_{NN}} = 2.76$ TeV and pp @ 7 TeV, deuteron
Flashing deuteron spectra

STAR, AuAu @ $\sqrt{s_{NN}} = 7.7 - 200$ GeV, deuteron

Transverse Momentum $p_T$ (GeV/c)

Deuterons

- 0-10% × $2^4$
- 10-20% × $2^3$
- 20-40% × $2^2$
- 40-60% × 2
- 60-80%
Flashin deuteron spectra

NA49, central PbPb, $\sqrt{s_{NN}} = 6.3 - 17.3$ GeV, deuteron

Can one obtain a physical picture out of these spectra? Yes!
Integrated spectra: midrapidity d/p ratio

Light nuclei are rare in relativistic HIC

“Penalty factor” at $\sqrt{s_{NN}} > 5$ GeV: $10^{-1} \rightarrow 3 \cdot 10^{-3}$
Form cluster if $m \leq |m_{inv}| \leq m + \Delta m$ and $|x_i - x_j| < D$

- $\Delta m$ and $D$ depend on nucleus
- the values are not specified in the publication
Hydro+coalescence


\[
E_A \frac{d^3 \tilde{N}_{N,Z}}{d^3 p_A} = \frac{N_{tot}^N Z_{tot}^Z}{A_{tot}^A} \left( \frac{P_{NZ}^3}{M_N A_{cell}} \right)^{A-1} \left( E \frac{d^3 \tilde{N}(N)}{d^3 p} \right)^A
\]

- 3-fluid hydrodynamics
- Computing coalescence spectra in every hydro cell
- Parameter $P_{NZ}$ fit to match yield
Hydro+coalescence


\[ E_A \frac{d^3 \tilde{N}_{N,Z}}{d^3 \tilde{P}_A} = \frac{N_{tot}^N Z_{tot}^Z}{A_{tot}^A} \left( \frac{P_{NZ}^3}{M_N A_{cell}} \right)^{A-1} \left( E \frac{d^3 \tilde{N}(N)}{d^3 p} \right)^A \]

- 3-fluid hydrodynamics
- Computing coalescence spectra in every hydro cell
- Parameter \( P_{NZ} \) fit to match yield
Most important deuteron production/disintegration reactions

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

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

| $X$  | $\sigma_{d+X}^{\text{inel}} \text{ [mb]}$ ($\sqrt{s} - \sqrt{s_{\text{thr}}} = [0.05, 0.25] \text{ GeV}$) | $\frac{dN^X}{dy} \big|_{y=0}$ |
|------|-------------------------------------------------|------------------|
| $\pi^{\pm}$ | 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

\[ \sigma_{pd}^\text{tot} - \sigma_{pd}^\text{el} \]

[Carlson et al]

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

SMASH

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

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

\[ 0 \quad 50 \quad 200 \quad 250 \]

\[ 2.8 \quad 2.85 \quad 2.9 \quad 2.95 \quad 3 \quad 3.05 \quad 3.1 \]

\[ Nd \leftrightarrow Nnp, \ \bar{N}d \leftrightarrow \bar{N}np: \text{ large cross-sections but not important at LHC energies, because } N \text{ and } \bar{N} \text{ are sparse} \]
Reactions of deuteron with (anti-)nucleons

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

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

SMASH

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

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

\[ 0 \quad 50 \quad 100 \quad 250 \quad 300 \quad 350 \]

\[ 2.8 \quad 2.9 \quad 3 \quad 3.1 \quad 3.2 \]

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

but not important at LHC energies, because \( N \) and \( \bar{N} \) 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

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

Reproducing $B_2$ without any free parameters
$p_T$-spectra for different centralities

\[ \frac{1}{N_{\text{ev}}} \frac{1}{2\pi p_T} \frac{d^2N}{dp_Tdy} \left[ \text{GeV}^{-2} \right] \]

\begin{itemize}
  \item 0-10% x4
  \item 10-20% x2
  \item 20-40%
  \item 40-60%
  \item 60-80%
\end{itemize}
$p_T$-spectra for different centralities

\[ \frac{1}{N_{\text{ev}}} \frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} \text{[GeV}^{-2}] \]\n
Pb+Pb, 2.76 TeV

- 0-10% x8
- 10-20% x4
- 20-40% x2
- 40-60%
- 60-80%
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: $\mu_B = \mu_B \frac{V}{V_0} \frac{a + V}{V_0}$, $a = 0.1$

$T_{\text{particlization}} = 155 \text{ MeV}$. 
Annihilation out of equilibrium: $\mu_B = \mu_B \frac{V/V_0}{a + V/V_0}$, $a = 0.1$

$T_{\text{particlization}} = 165$ MeV. Qualitatively similar to our simulation.