(Anti-)nuclei production and flow in pp, p–Pb and Pb–Pb collisions with ALICE

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Production of nuclei

- Significant amount of light (anti-)nuclei is produced in pp, p–Pb and Pb–Pb collisions at the LHC
- Production mechanism not completely understood
  - Separation energy $E_S = O(1 \text{ MeV})$ small compared to the kinetic freeze-out temperature ($T_{fo} \sim 100 \text{ MeV}$)
  - No first principle calculation possible
- Two classes of phenomenological models
  - Statistical Hadronization Model (SHM)
  - Coalescence model
Statistical Hadronisation Model

- Hadrons are emitted from a medium in statistical equilibrium at chemical freeze-out
- \[ \frac{dN}{dy} \propto \exp(-m/T_{ch}) \]
  \[ \Rightarrow \] Strong dependence on \( T_{ch} \) for nuclei
- \( \text{Pb-Pb}: \) grand canonical ensemble
- Small systems: local conservation of quantum numbers is necessary
  \[ \Rightarrow \] Canonical ensemble
Coalescence approach

- At the kinetic freeze-out, baryons close by in phase space can form a nucleus

- Coalescence parameter $B_A$ is the key parameter
  
  \[ E_A \frac{d^3N_A}{dp^3_A} = B_A \left( E_p \frac{d^3N_p}{dp^3_p} \right)^A \bigg|_{\vec{p}_p=\vec{p}_{A/A}} \]

- $B_A$ is related to the production probability

- $B_A$ is calculable via the Wigner formalism without free parameters
The ALICE detector

- General purpose heavy-ion experiment
- Excellent tracking and particle identification (PID) capabilities
- Low material budget
- Best suited detector for studies of (anti-)nuclei production at the LHC
The ALICE detector

- Multiplicity / centrality estimation
- Tracking and Vertex reconstruction
- Separation of primary and secondary vertices
- Separation of secondary nuclei (from spallation reactions)
Particle identification

Time Projection Chamber

- Tracking
- PID via $dE/dx$ measurement

Raw yield extraction

- From $n\sigma$ distribution for each $p_T$ interval
Particle identification

**Time Of Flight**

- PID via $\beta$ measurement

**Raw yield extraction**

- From TOF $m^2$ distribution for each $p_T$ interval

ALICE Performance
antideuteron, pp, $\sqrt{s} = 13$ TeV
V0M Multiplicity Class II
$2.0 \leq p_T < 2.2$ GeV/c

Counts / (0.08 GeV^2/c^4)

ALICE Performance
Pb-Pb $\sqrt{S_{NN}} = 5.02$ TeV

ALI-PERF-106336
ALI-PERF-146215
Deuteron and $^3$He spectra in Pb–Pb

$\text{Pb–Pb, } \sqrt{s_{NN}} = 5 \text{ TeV}$

- $p_T$ spectra fitted with Blast-Wave function $\Rightarrow$ Extrapolation to unmeasured regions

- Hardening with increasing centrality $\Rightarrow$ Collective motion (radial flow)
  - Consistent with both coalescence and SHM (hydrodynamics + hadron resonance gas model)
Deuteron and $^3$He elliptic flow $v_2$

$$\frac{d^3N}{dp^3} \propto (1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n)))$$

Pb–Pb, $\sqrt{s_{NN}} = 5$ TeV

- Mass ordering at low $p_T$, increasing trend with $p_T$ and for more peripheral events
- Expectations from relativistic hydrodynamics are fulfilled
Comparison to simplified models

\[ \frac{d^3N}{dp^3} \propto (1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))) \]

- \( v_2 \) of (anti-)\(^3\)He lies in between Blast-Wave and naive coalescence
  - Simplified hydrodynamic and coalescence models do not describe the data
Comparison to state-of-the-art coalescence

- Hydrodynamical simulation (iEBE-VISHNU) + coalescence ([Wenbin, PRC 98, 054905 (2018)])
  - Good description of the deuteron $v_2$ and $v_3$ as well as the $^3$He $v_2$ in 0-40%

- No predictions available for more peripheral collisions or SHM
Deuteron spectra in p–Pb

- Fit with Blast-Wave function unstable
- $p_T$ spectra fitted with $m_T$-exponential function
- Hardening less pronounced than in Pb–Pb
Deuteron spectra in pp

\[ \frac{d^2N}{dp_T^2 dy} \propto \frac{(n - 1)(n - 2)}{nC [nC + m(n - 2)]} \left( 1 + \frac{m_T - m}{nC} \right)^{-n} \]

- \( p_T \) spectra fitted with Lévy-Tsallis\(^1 \) function
  \( \Rightarrow \) Extrapolation to unmeasured regions
- Hardening less pronounced than in Pb–Pb
Ratio to protons

- Continuous evolution with multiplicity
  ⇒ Smooth transition from small to large system size
  ⇒ Single underlying production mechanism?

- Increasing trend at low and intermediate multiplicities
  • SHM: Canonical suppression ⇔ Tension\(^1\) for ALICE p/π
  • Coalescence: increasing phase space

- No dependence of the ratio on multiplicity for high multiplicities
  • In agreement with both SHM and coalescence
  • Coalescence prediction below data for \(^3\)He

\(^1\)Vovchenko, arXiv: 1906.03145
Coalescence parameter $B_A$

Measurements in pp are compatible with a flat $B_A$ predicted by naive coalescence

Trend with $p_T/A$ in p–Pb and Pb–Pb collisions described by recent hydrodynamic calculations with afterburner (Oliinychenko, PRC 99, 044907 (2019))

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Coalescence parameter $B_A$

- Continuous evolution of $B_A$ with multiplicity
  $\Rightarrow$ Smooth transition from small to large system size
  $\Rightarrow$ Single underlying production mechanism?
- Advanced coalescence taking the size of the nucleus and the emitting source into account predicts a similar trend
Conclusions

• ALICE has measured the production of light (anti-)nuclei in different collision systems and at different energies

• Measurements of the ratio-to-protons as well as the coalescence parameter as a function of the multiplicity show a smooth transition from small to large system size
  • Canonical Statistical Model can describe the evolution of the ratio-to-protons but there is some tension with the measured $p/\pi$ ratio
  • Coalescence has difficulties to describe the data at high multiplicities

• State-of-the-art coalescence describes the flow of deuterons and $^3$He
  • SHM predictions (hydrodynamics + hadron resonance gas model) are not available

⇒ More precise data and models are needed to clarify the production mechanism of light (anti-)nuclei

Thank you for your attention!
Back-up
Removal of secondary nuclei

- Secondary nuclei from spallation affect the signal at low $p_T$
- Distance-of-closest approach to the primary vertex distribution should be flat
- Peak around zero due to wrong assignment of ITS cluster
- Fraction of primary nuclei obtained via fits of MC templates
Anti-$^4$He production in Pb–Pb

- Anti-$^4$He yield has been measured in Pb–Pb collisions
Anti-\(^4\)He production in Pb–Pb

- Anti-\(^4\)He yield has been measured in Pb–Pb collisions
- Exponential decrease in particle rate predicted by thermal model is confirmed
- Penalty factor:
  - Pb–Pb collisions: \(~300\)
  - p–Pb collisions: \(~600\)
  - pp collisions: \(~1000\)
Anti-Nuclei / nuclei ratio

- $\mu_B \sim 0$ at LHC energies
  \[ \Rightarrow \text{Anti-nucleus/nucleus ratio is expected to be compatible with unity} \]

- Measured $\bar{d}/d$ and $^{3}\text{He}/^{3}\text{He}$ in Pb–Pb, p–Pb and pp collisions confirm this prediction
  \[ \Rightarrow \text{Matter and anti-matter is produced in the same amount} \]
Deuteron $\nu_3$

- Both expectations from relativistic hydrodynamics are fulfilled
  - Mass ordering at low $p_T$
  - Slower rise for heavier particles
$n_q$-scaling of light (anti-)nuclei $v_2$

- Baryons follow an approximate scaling vs $p_T/n_q$
- Baryons and mesons show an approximate scaling vs $E^{\text{kin}}_T/n_q$