Probes of hadronization
(resonances, (hyper)nuclei, charm baryons, coalescence)

Ramona Lea on behalf of the ALICE Collaboration
*Physics Department, University and INFN Trieste*
Evolution of a heavy ion collision

- Two Lorentz contracted nuclei approach and collide
- "Pre-equilibrium"
- Formation of Quark-Gluon Plasma phase (if $T > T_c$)
- Phase transition from QGP to hadron gas ($T_c \approx 160$ MeV)
- Chemical freeze-out ($T_{\text{chem}} \sim 156$ MeV):
  - inelastic reactions cease: the chemical composition of the system is fixed (particle yields and fluctuations)
- Kinetic freeze-out ($T_{\text{kin}} \sim 100$ MeV)
  - elastic reactions cease: spectra and correlations are frozen (free streaming of hadrons)
Thermal model fit to LHC data

- Hadron abundances in HI (yields and ratios) can be successfully interpreted in terms of production at chemical equilibrium.
- Statistical (thermal) models predict the yields of any particle at chemical freeze-out once that $T_{\text{ch}}$ and $\mu_B$ are known.
- At the LHC ($\mu_B = 0$) particle yields of light flavor hadrons (including nuclei) are described within the thermal model with a common chemical freeze-out temperature ($T_{\text{ch}} = 156 \pm 2$ MeV).

K* not included in the fit.
Resonances
Thermal model fit to ALICE data

- Hadron abundances in HI (yields and ratios) can be successfully interpreted in terms of production at chemical equilibrium.
- Statistical (thermal) models predict the yields of any particle at chemical freeze-out once that $T_{\text{chem}}$ and $\mu_B$ are known.
- At the LHC ($\mu_B = 0$) particle yields of light flavor hadrons (including nuclei) are described within the thermal model with a common chemical freeze-out temperature ($T_{\text{chem}} = 156 \pm 2$ MeV).
- $K^*(892)$ production not described (yield suppressed)

Hadronic phase

The yield of resonances produced in heavy ion collisions is expected to be in agreement with $T_{\text{ch}}$ chemical freeze-out equilibrium.

Although, can be altered by hadronic interactions between chemical and kinetic freezeouts:

- **rescattering**: daughter particles undergo elastic scattering or pseudo-elastic scattering through a different resonance → parent particle is not reconstructed → loss of signal
- **regeneration**: pseudo-elastic scattering of decay products ($\pi K \rightarrow K^*0$, $KK \rightarrow \phi$, etc.) → increased yields

Effect of hadronic processes depends on:

- lifetime and density of hadronic phase
- resonance lifetime and scattering cross sections
Light flavoured hadronic resonances

<table>
<thead>
<tr>
<th></th>
<th>(\rho(770)^0)</th>
<th>(K^*(892)^0)</th>
<th>(\Lambda(1520))</th>
<th>(\phi(1020))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c\tau (\text{fm}/c))</td>
<td>1.3</td>
<td>4.2</td>
<td>12.6</td>
<td>46.2</td>
</tr>
</tbody>
</table>

- Resonances have lifetimes comparable to that of the fireball produced in heavy-ion collisions:
  - can be used to study **properties** and **lifetime** of the late **hadronic phase**
- Resonances differ by mass and quark content:
  - **insights** on the multiplicity-dependent **enhancement** of **strangeness** production
  - **anomalous** baryon-to-meson **ratios** at **intermediate transverse momentum** parton energy loss
Suppression of hadronic resonances

<table>
<thead>
<tr>
<th>$\rho(770)^0$</th>
<th>$K^*(892)^0$</th>
<th>$\Lambda(1520)$</th>
<th>$\phi(1020)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ct (fm/c)</td>
<td>1.3</td>
<td>4.2</td>
<td>12.6</td>
</tr>
</tbody>
</table>

- $\rho(770)^0/\pi^\pm$
  - The ratio of $p_T$ integrated yields divided by particle with similar quark content $\rho/\pi$ shows clear suppression going from pp and peripheral Pb-Pb collisions to central Pb-Pb

![Particle Yield Ratios](image)
Suppression of hadronic resonances

<table>
<thead>
<tr>
<th></th>
<th>$\rho(770)^0$</th>
<th>$K^*(892)^0$</th>
<th>$\Lambda(1520)$</th>
<th>$\phi(1020)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c\tau (\text{fm}/c)$</td>
<td>1.3</td>
<td>4.2</td>
<td>12.6</td>
<td>46.2</td>
</tr>
</tbody>
</table>

- $K^*(892)^0/K^\pm$
  - $K^*(892)/K$ ratio decreases as function of multiplicity
  - Suggests that re-scattering is dominant over regeneration

Suppression of hadronic resonances

<table>
<thead>
<tr>
<th></th>
<th>$\rho(770)^0$</th>
<th>$K^*(892)^0$</th>
<th>$\Lambda(1520)$</th>
<th>$\phi(1020)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$(fm/c)</td>
<td>1.3</td>
<td>4.2</td>
<td>12.6</td>
<td>46.2</td>
</tr>
</tbody>
</table>

• $\Lambda(1520)/\Lambda$
  • $\Lambda(1520)/\Lambda$ ratio clearly decreases as function of multiplicity in Pb-Pb
  • Clear suppression compared to the thermal model predictions


ALICE Preliminary
- pp $\sqrt{s} = 7$ TeV
- Pb-Pb $\sqrt{s}_{NN} = 5.02$ TeV
- Xe-Xe $\sqrt{s}_{NN} = 5.44$ TeV

ALICE
- pp $\sqrt{s} = 2.76$ TeV
- pp $\sqrt{s} = 7$ TeV
- Pb-Pb $\sqrt{s}_{NN} = 2.76$ TeV

STAR
- pp $\sqrt{s} = 200$ GeV
- Au-Au $\sqrt{s}_{NN} = 200$ GeV

EPOS3
- EPOS3 (UWMD OFF)
Suppression of hadronic resonances

<table>
<thead>
<tr>
<th></th>
<th>$\rho(770)^0$</th>
<th>$K*(892)^0$</th>
<th>$\Lambda(1520)$</th>
<th>$\phi(1020)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c\tau(fm/c)$</td>
<td>1.3</td>
<td>4.2</td>
<td>12.6</td>
<td>46.2</td>
</tr>
</tbody>
</table>

- $\phi(1020)/K^+$
  - $\phi(1020)/K$ ratio independent of collision system (energy)
  - The ratio $\phi(1020)/K$ increases at large $\langle dN_{ch}/d\eta \rangle$ because of strangeness enhancement

Suppression of hadronic resonances

• Hadronic Resonances:
  - Suppression of $\rho^0$, $K^{*0}$, $\Lambda(1520)$, while $\phi$ not suppressed
  - Qualitative description is obtained with EPOS+UrQMD
    - Hadronic phase (UrQMD) important in EPOS to describe data
  - Consistent results for Xe-Xe and Pb-Pb at similar multiplicity
  - Indication of the existence of a hadronic phase
Light (hyper-)nuclei
Deuteron $p_T$ spectra in Pb-Pb collisions

Spectra are extracted in several centrality bins and fitted with blast-wave function for the extraction of yields

$^4\text{He}$ production in Pb-Pb collisions

- Heaviest anti-nucleus observed: 16 candidates in Pb-Pb at 5.02 TeV
- Pre-selection using $dE/dx$ measured in TPC
- Selection: $\pm 3\sigma$ from the expected value for $^4\text{He}$
- Signal extraction from mass squared distribution obtained using TOF
Nuclei production in Pb – Pb collisions

\[dN/dy \propto \exp\left(-\frac{m}{T_{\text{chem}}}\right)\]

- Thermal model prediction: exponential dependence of the yield

\[\frac{n_i}{n_{i+1}} \approx \exp\left(-\frac{\Delta m}{T_{\text{chem}}}\right)\]

The density ratio of a particle with the next heavier one:

\[(m_p - m_d) \sim 938 \text{ MeV} \]
\[p/d \sim \exp(938/160) \sim 350\]

Thermal model expectation

**Experimental result**

\[p/d \sim \exp(-B) \sim 330^{+70}_{-61}\]

Hypernuclei

- A hypernucleus is a nucleus which contains at least one hyperon (a baryon containing one or more strange quarks) in addition to nucleons

- **Main goals of hypernuclear physics:**
  - Extension of nuclear chart
  - Understand the baryon-baryon interaction in strangeness sector
  - Study the structure of multi-strange systems
Hypernuclei

- A hypernucleus is a nucleus which contains at least one hyperon (a baryon containing one or more strange quarks) in addition to nucleons.

- **Main goals of hypernuclear physics:**
  - Extension of nuclear chart
  - Understand the baryon-baryon interaction in strangeness sector
  - Study the structure of multi-strange systems

$^3\Lambda\bar{p}$ is the lightest known hypernucleus and is formed by $(p,n,\Lambda)$.

- Mass = 2.991 GeV/c$^2$
- $B_\Lambda = 0.13 \pm 0.05$ MeV ($B_d = 2.2$ MeV, $B_t = 8.5$ MeV, $B_{^3\text{He}} = 7.7$ MeV)

$(^3\Lambda\bar{p})\ ^3\Lambda\bar{p}$ is unstable under weak decay and branching ratios are not well known → Only few theoretical calculations available [1]

Thermal model comparison

- $^3\Lambda H/^3He$ ratio compared with different thermal models:
- Extracted yield is in good agreement with equilibrium thermal model prediction for $T_{\text{chem}} = 156$ MeV, such as GSI-Heidelberg model [1] even if $B_{\Lambda} < < T_{\text{ch}}$

\[ ^3\Lambda H \rightarrow (^3\text{He} + \pi) \text{ assuming B.R.}=25\% \]


- Opposite to resonances, yields of (hyper)nuclei are described by the common chemical freeze-out temperature ($T_{\text{chem}} = 156 \pm 2$ MeV)
- The binding energy of (hyper)nuclei is very small and it is surprising that they do not immediately dissociate in the hadronic phase
  - $T_{\text{ch}}$ (160 MeV) < $T_{\text{hadronic}}$ < $T_{\text{kin}}$ (100 MeV)

K* not included in the fit
Coalescence Model

FIG. 1. Schematic for the production of a deuteron in the final state of a relativistic collision between two heavy nuclei.
Coalescence model

- Model originally developed to describe light-nuclei production (deuteron, triton...)
- If baryons at freeze-out are close enough in phase space and match spin state a (anti-)nucleus can be formed
- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space
- Assuming that p and n have the same mass and have the same $p_T$ spectra, the yield of any nucleus can be determined as

\[
E_A \frac{d^3N_A}{dp_A^3} = B_A \left( E_p \frac{d^3N_p}{dp_p^3} \right)^A
\]

\[
B_A = \left( \frac{4\pi}{3} \frac{p_0^3}{p_p^3} \right)^{(A-1)} \frac{1}{A! m_A^A}
\]
Coalescence model

- Model originally developed to describe light-nuclei production (deuteron, triton...)
- If baryons at freeze-out are close enough in phase space and match spin state a (anti-)nucleus can be formed
- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space
- Assuming that p and n have the same mass and have the same $p_T$ spectra, the yield of any nucleus can be determined as

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left( \frac{d^3N_p}{dp_p^3} \right)^A$$

$$B_A = \left( \frac{4\pi}{3} p_0^3 \right)^{(A-1)} \frac{1}{A!} \frac{M}{m^A}$$
Coalescence model

- Model originally developed to describe light-nuclei production (deuteron, triton...)
- If baryons at freeze-out are close enough in phase space and match spin state a (anti-)nucleus can be formed
- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space
- Assuming that $p$ and $n$ have the same mass and have the same $p_T$ spectra, the yield of any nucleus can be determined as

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left( E_p \frac{d^3N_p}{dp_p^3} \right)^A$$

$$B_A = \left( \frac{4\pi}{3} \frac{p_0^3}{A} \right)^{(A-1)} \frac{1}{A! \, m^A}$$
Coalescence model

- Model originally developed to describe light-nuclei production (deuteron, triton...)
- If baryons at freeze-out are close enough in phase space and match spin state a (anti-)nucleus can be formed
- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space
- Assuming that p and n have the same mass and have the same $p_T$ spectra, the yield of any nucleus can be determined as

$$\frac{p_T}{A} = 0.75 \text{ GeV/c}$$

$$E_A \frac{d^3 N_A}{d p_A^3} = B_A \left( E_p \frac{d^3 N_p}{d p_p^3} \right)^A$$

$$B_A = \left( \frac{4 \pi}{3} p_0^3 \right)^{(A-1)} \frac{1}{A! m^A}$$
Coalescence parameter $B_2$

**Simple** coalescence model
- Flat $B_2$ vs $p_T$ and no dependence on multiplicity/centrality
- ✔ Approximately observed in “small systems”: pp, p-Pb and peripheral Pb-Pb

![Graph showing $B_2$ vs multiplicity with data points for pp, p-Pb, and Pb-Pb at different energies.](image)

- ALICE Preliminary
- $p_T/A = 0.75$ GeV/c
- $\langle dN_{ch} / d\eta_{lab} \rangle |_{|\eta_{lab}| < 0.5}$
- V0M Multiplicity Classes
  - d, pp, $\sqrt{s} = 13$ TeV
  - d+\bar{d}, pp, $\sqrt{s} = 7$ TeV
- V0A Multiplicity Classes (Pb-side)
  - d, Pb-Pb, $\sqrt{s_{NN}} = 5.02$ TeV
  - d, Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV (PRC 93 (2015) 024917)
**Coalescence parameter $B_2$**

**Simple** coalescence model
- Flat $B_2$ vs $p_T$ and no dependence on multiplicity/centrality
  - ✔ Approximately observed in “small systems”: pp, p-Pb and peripheral Pb-Pb

**More elaborate** coalescence model takes into account the volume of the source:

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

- $B_2$ scales like HBT radii ($R$)
  - ✔ decrease with centrality in Pb-Pb is explained as an increase in the source volume
  - ✔ increase with $p_T$ in central Pb-Pb reflects the $k_T$-dependence of the homogeneity volume (i.e. volume with similar flow properties) in HBT
  - ✔ Qualitative agreement in central Pb-Pb collisions

---

K. Blum et al., PRD 96 (2017) 103021
Light nuclei production: Deuteron to proton ratio

- \( d/p \) increases with multiplicity going from pp to peripheral Pb-Pb: consistent with simple coalescence (\( d \propto p^2 \))
- No significant centrality dependence in Pb-Pb: consistent with thermal model (yield fixed by \( T_{\text{chem}} \))
- How the two models are connected is not yet fully understood
  - Is there a single particle production mechanism?
Charm Baryon
Heavy quarks in heavy ion collisions

- Charm and beauty quarks are produced in parton hard scatterings in the initial phase of the heavy-ion collision (production time of $c\bar{c}(b\bar{b})$ pair at rest)
- Flavour is conserved in strong interactions → Transported through the full system evolution

- What can be tested?
  - In-medium energy loss: colour-charge and quark-mass dependence
  - Heavy quark participation in the collective expansion, thermalisation in the medium
  - Modification of the hadronization mechanisms in the medium
$\Lambda_c$ production in heavy ion collisions

- ALICE measured $\Lambda_c$ in Pb-Pb collisions at 5.02 TeV for 0-80% centrality class
- 2.5σ hint of $\Lambda_c/D^0$ ratio enhanced in Pb-Pb collisions w.r.t. pp and p-Pb collisions
  - Coalescence production mechanism at play
\( \Lambda_c \) production in heavy ion collisions

- ALICE measured \( \Lambda_c \) in Pb-Pb collisions at 5.02 TeV for 0-80% centrality class
  - \( \sim 2.5 \sigma \) hint of \( \Lambda_c / D^0 \) ratio enhanced in Pb-Pb collisions w.r.t. pp and p-Pb collisions
  - \( \sim 2.0 \sigma \) hint of larger \( R_{AA}^{\Lambda_c} \) of \( \Lambda_c \) than D mesons in 0-10% centrality class
    - Charm quark hadronization via coalescence:
      - hierarchy of the \( R_{AA}^{\Lambda_c} > D_s > \) Non-strange D-meson > pions

ALICE Collaboration arXiv:1809.10922
DOI: 10.1016/j.physletb.2019.04.046
CMS measured $\Lambda_c^+$ production in 2 centrality intervals (0-30%) and (30-50%) in the $p_T$ interval 10-20 GeV/c:
- The $R_{AA}$ for $\Lambda_c^+$ show a hint of suppressed production of $\Lambda_c^+$ for $p_T > 10$ GeV/c (0-100%), but no conclusion can be drawn due to the large uncertainty in the pp differential cross section.
The $\Lambda_c / D^0$ ratio in Pb-Pb collisions, is consistent with the result from pp collisions:

- Result in contrast w.r.t ALICE observation of a large enhancement in the $\Lambda_c / D^0$ ratio in the $p_T$ range of 6-12 GeV/c
  - may suggest that there is no significant contribution from the coalescence process for $p_T > 10$ GeV/c in Pb-Pb collisions

CMS Collaboration CMS PAS HI-18-009
Conclusions

- **Thermal models** are able to describe the production yields of light flavor hadrons and (hyper)nuclei within a **common chemical freeze-out temperature**
- Resonance results support the **existence** of a **hadronic phase** in central heavy-ion collisions that lasts long enough to cause a significant reduction of the reconstructed yields of short lived resonances: surprisingly **nuclei** seem to **survive** thru this phase
- Light nuclei measurement reveals **system size dependence** of **hadronization**:
  - Evolution of $B_A$ and $d/p$ ratio vs multiplicity: is there a **single** particle production mechanism?
- Charmed-baryon $\Lambda_c$ is less suppressed than D mesons: favored production mechanism is quark **coalescence** for $p_T < 10 \text{ GeV}/c$, for higher momenta this has not been observed
- **Beautiful picture, but there is still a lot to do and to understand!**
  ➢ New and more precise data can be expected from the LHC on the presented topics in the next years
Extra Material
Production of light (anti-)(hyper)nuclei

After the Long Shutdown 2 data will be collected with better performance at higher luminosity

- Expected integrated luminosity: $\sim 10 \text{ nb}^{-1}$ ($\sim 8 \times 10^9$ collisions in the 0-10% centrality class)
- Precision test of coalescence / thermal production models
- Sensitive to size ratio of the object and the source
- Search for rarely produced anti- and hypermatter: Insights on the strength of the hyperon-nucleon interaction, relevant for nuclear physics and neutron stars.
• Charm quark number is conserved in strong interaction
• Hadronization chemistry: crucial for the interpretation of the heavy flavor hadron spectra
• Run 3+4 data will allow the first comprehensive survey of this effect
• $D_s$, $B_s$ and $Λ_c$ spectra from low to high $p_T$ in Pb-Pb collisions
• Provide the necessary statistical accuracy to see the emergence of the effect at low $p_T$
Identification of nuclei

Low momenta: specific energy loss in the TPC
- Nuclei identification via $dE/dx$ measurement in the TPC:
  - Excellent separation of (anti-)nuclei from other particles over a wide range of momenta

Higher momenta: time-of-flight measurement in the TOF
- Velocity measurement with the Time Of Flight detector is used to evaluate the $m^2$ distribution
- Excellent TOF performance: $\sigma_{\text{TOF}} \approx 85$ ps in Pb-Pb collisions

“More elaborate” coalescence model

- For “large” systems, the size of the emitting volume ($V_{\text{eff}}$) has to be taken into account:
  - the larger the distance between the protons and neutrons which are created in the collision, the less likely it is that they coalesce
- The source can be parameterized as rapidly expanding under radial flow (hydro)
- The coalescence process is governed by the same correlation volume (“length of homogeneity”) which can be extracted from HBT interferometry
- The source radius enters in the $B_A$ and in the quantum-mechanical correction $\langle C_A \rangle$ factor that accounts for the size of the object being produced ($d$, $^3\text{He}$, ...)

$$B_A = \frac{2J_A+1}{2^A} A \langle C_A \rangle \frac{V_{\text{eff}}(A, M_t)}{V_{\text{eff}}(1, m_t)} \left( \frac{(2\pi)^3}{m_t V_{\text{eff}}(1, m_t)} \right)^{A-1}$$

K. Blum et al., PRD 96 (2017) 103021

Good description of the data
Centrality of the collisions

Centrality = degree of overlap of the 2 colliding nuclei

Central collisions:  
- small impact parameter \( b \)  
- high number of participant nucleons \( \rightarrow \) high multiplicity

Peripheral collisions:  
- large impact parameter \( b \)  
- low number of participant nucleons \( \rightarrow \) low multiplicity

Centrality connected to observables via Glauber model

Centrality of the collisions: p-Pb and pp

Multiplicity estimator: slices in VZERO-A (V0A) amplitude

Correlation between impact parameter and multiplicity is not as straightforward as in Pb-Pb.
Statistical thermal model

- Thermodynamic approach to particle production in heavy-ion collision: all the particles are produced at chemical freeze-out
- Starting point: Grand Canonical partition function ($Z$) for a relativistic ideal quantum gas of hadrons of particle type $i$ ($i =$ pion, proton,... → full PDG)
- Thermal model can predict also the yields of any particle at chemical freeze-out
- Exponential dependence of the particle yield: $\frac{dN}{dy} \propto e^{-\frac{m}{T_{chem}}}$
- The thermal model predicts an exponential decrease of particle yields with increasing mass at a given temperature
- The density ratio of a particle with the next heavier one: $\frac{n_i}{n_{i+1}} \approx \exp\left(-\frac{\Delta m}{T}\right)$
Thermal model

Statistical hadronization model: thermal emission from equilibrated source

Particle abundances fixed at chemical freeze-out

\[ N_i = \frac{g_i V}{2\pi^2} \int_0^{+\infty} \frac{p^2 dp}{\exp \left[-\left(\frac{E-\mu_B}{T_{\text{chem}}}\right)\right]} \pm 1 \]

- Primordial yields modified by hadron decays:
  - Contribution obtained from calculations based on known hadron spectrum
  - Excellent agreement with data with only 2 free parameters: \( T_{\text{chem}}, V \)

Coalescence parameter $B_3$

$B_3$ of ($\bar{t}$)t and ($^3\text{He}$)$^3$He measured in pp and Pb-Pb collisions

First ever measurements of the $B_3$ of $\bar{t}$ and $^3\text{He}$ in pp collisions

Increasing trend with $p_T$ and centrality observed in Pb-Pb collision
Hypertriton ($^3\_\Lambda\_H$)

$^3\_\Lambda\_H$ is the lightest known hypernucleus and is formed by $(p,n,\Lambda)$.

- Mass = 2.991 GeV/$c^2$
- $B_{\Lambda} = 0.13 \pm 0.05$ MeV ($B_d = 2.2$ MeV, $B_t = 8.5$ MeV, $B_{\_3^\_He} = 7.7$ MeV)

($^3\_\Lambda\_H$) $^3\_\Lambda\_H$ is unstable under weak decay. Possible decay modes:

- $^3\_\Lambda\_H \rightarrow ^3\_He + \pi^-$ (~25%)
- $^3\_\Lambda\_H \rightarrow ^3\_H + \pi^0$ (~13%)
- $^3\_\Lambda\_H \rightarrow d + p + \pi^-$ (~41%)
- $^3\_\Lambda\_H \rightarrow d + n + \pi^0$ (~21%)

Branching ratios are not well known
Only few theoretical calculations\cite{1} available

\cite{1} Kamada et al., Phys. Rev. C57(1998)4