Cluster formation near mid rapidity — can the mechanism be identified experimentally?

Viktar Kireyeu for the PHQMD team
Cluster formation in heavy-ion collisions

(Anti)hypernuclei production:
- at mid-rapidity by $\Lambda$ coalescence during expansion
- at projectile/target rapidity by re-scattering/absorption of $\Lambda$ by spectators

«Ice in a fire» puzzle: how the weakly bound objects can be formed and survive in a hot environment?
Modelling of cluster formation in HIC

Statistical models
- Production of nuclei depending on $T$ and $\mu_B$ at chemical freeze-out & particle mass

Coalescence models
- Formation of nuclei by nucleons & hyperons that are close in coordinate and momentum spaces at freeze-out time

$\Rightarrow$ no dynamical cluster formation during time evolution
$\Rightarrow$ no information on the dynamics of clusters formation & microscopic origin

In order to understand the microscopic origin of cluster formation one needs a realistic model for the dynamical time evolution of the HIC

Transport models — dynamical modelling of cluster formation based on interactions:
  via potential interaction — ‘potential‘ mechanism
  by scattering — ‘kinetic‘ mechanism
Parton-Hadron-Quantum-Molecular Dynamics

= n-body microscopic transport approach for the description of heavy-ion dynamics with dynamical cluster formation from low to ultra-relativistic energies

- Initial A+A collisions
- Formation of QGP
- Partonic phase
- Hadronization
- Hadronic phase

Relativistic considerations + Correlations between nucleons + Cluster recognition

QMD
- Initialization nuclei
- propagation of baryons

PHSD
- Primary collisions
- pre-hadronic states

local $\varepsilon > \varepsilon_c$ dissolution of pre-hadrons

Cluster recognition

MST or SACA

J. Aichelinet al., PRC 101 (2020) 044905

Cluster criterion: distance of nuclei
Algorithm: search for accumulations of particles in coordinate space

1. Two particles i & j are bound if:
   \[ |r_i - r_j| < 4.0 \text{ fm} \]

2. Particle is bound to cluster if bound with at least one particle of cluster

Remark: additional momentum cuts lead to a small changes: particles with large relative momentum are mostly not at the same position (V. Kireyeu, Phys.Rev.C 103 (2021) 5, 054905).
Cluster stability over time

QMD can not describe clusters as ‘quantum objects’
the cluster **quantum ground state** has to respect a minimal average kinetic energy of
the nucleons while the semi-classical (QMD) ground state - not!
nucleons may still be emitted from the QMD clusters while in the corresponding
quantum system this is not possible
thus, a cluster which is “bound” at time $t$ can **spontaneously** dissolve at $t + \Delta t$

= QMD clusters are not fully stable over time:
the multiplicity of clusters is time dependent
the form of the final rapidity, $pT$ distribution and ratio of particles do not change with

How to stabilize QMD clusters?

**Scenario 1:** S. Glässel et al., PRC 105 (2022) 1, 014908

PHQMD results are taken at ‘physical time’:
$t = t_0 \cosh(y)$

where $t_0$ is the time selected as a best description of the
cluster multiplicity at $y=0$
Cluster stability over time

The PHQMD results for d and $^3$He agree with NA49 and STAR data.

$\sqrt{s_{NN}} = 8.8$ GeV

$\sqrt{s_{NN}} = 7.7$ GeV – 200 GeV

$\begin{align*}
    t &= t_0 \cosh(y), \\
    t_0 &= 53 \text{ fm/c for d} \\
    t &= t_0 \cosh(y), \\
    t_0 &= 67 \text{ fm/c for } ^3\text{He}
\end{align*}$


S. Gläßel et al., PRC 105 (2022) 1, 014908
Cluster stability over time

Scenario 2:
G. Coci et al., PRC 108 (2023) 1, 014902

Stabilisation Procedure:

- consider asymptotic state: clusters and free nucleons

- For each nucleon in MST track the freezout-time = time at which the last collision occurred

- Recombine nucleons into clusters with $E_B < 0$ if time of cluster disintegration is larger than nucleon freeze-out time

Allows to recover most of “lost” clusters

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<th>$t_1$</th>
<th>$t_2$</th>
<th>$t_3$</th>
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<td>before stabilisation</td>
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<tr>
<td>after stabilisation</td>
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![Graph showing dN/dy over time for different scenarios](image)
N+N+π inclusion of all possible channels allowed by total isospin T conservation:

- Hierarchy due to large π abundance
  \[ \pi^+ + N + N \rightarrow \pi^+ + d \gg N + p + n \rightarrow N + d \]
- Inclusion of all isospin channels enhances deuteron yield ~ 50%.
- \( p_T \) slope is not affected

**RHIC BES energy \( \sqrt{s} = 7.7 \text{ GeV} \):**

**GSI SIS energy \( \sqrt{s} < 3 \text{ GeV} \):**

- Baryon dominated matter
- Enhancement due to inclusion of isospin \( \pi + N + N \) channels is negligible
Kinetic mechanism for deuteron formation

1) the finite-size of $d$ in the coordinate space ($d$ is not a point-like particle) – for in-medium $d$ production: assume that a deuteron can not be formed in a high density region, i.e. if there are other particles (hadrons or partons) inside the ‘excluded volume’.

Excluded volume condition: $\vec{r}(i)^* - \vec{r}(d)^* < R_d$

2) the momentum correlations of $p$ and $n$ inside $d$: QM properties of deuteron must be also in momentum space -> momentum correlations of pn-pair

- For a “candidate” deuteron calculate the relative momentum $p$ of the interacting pn-pair in the deuteron rest frame
- The probability of the pn-pair to bind into a final deuteron with momentum $p$ is given by the projection on DWF

Strong reduction of $d$ production

$p_T$ slope is not affected by excluded volume condition

Strong reduction of $d$ production by projection on DWF
Kinetic mechanism for deuteron formation

Total deuteron production = Kinetic mechanism with finite-size effects + MST (with stabilization) identification of deuterons ("stable" bound \( E_B < 0 \), \( A=2, Z=1 \) clusters)

Finite-size effects for kinetic deuterons:

1) excluded-volume
2) Momentum projection
3) both effects
Where clusters are formed?

- Coalescence and MST give very similar multiplicities and y- and pT–distributions
- PHQMD and UrQMD results in the cascade mode are very similar
- Deuteron production is sensitive to the realization of potential in transport approaches

Coalescence as well as the MST procedure show that the deuterons remain in transverse direction closer to the center of the heavy-ion collision than free nucleons.

Deuterons are behind the fast nucleons.

V. Kireyeu et al., PRC 105 (2022) 044909
Can the deuteron formation mechanism be identified experimentally?

V. Kireyeu et. al, arxiv:2304.12019

- At mid-rapidity only ~50% of coalescence deuterons (at freeze-out) are found by MST.
- Rapidity distribution has a different shape.
- Transverse momentum distributions has different slope at low $p_T$
Summary

- **The PHQMD** is a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster and hypernuclei formation.

- Clusters are formed **dynamically by potential interactions** among nucleons and hyperons and identified by Minimum Spanning Tree model.

- **Kinetic mechanism** for deuteron production is implemented in the PHQMD with inclusion of full isospin decomposition for hadronic reactions which enhances d production.

- However, accounting for the quantum properties of the deuteron, modelled by the finite-size excluded volume effect in coordinate space and projection of relative momentum of the interacting pair of nucleons on the deuteron wave-function in momentum space, leads to a strong reduction of d production, especially at target/projectile rapidities.

- The PHQMD reproduces cluster and hypernuclei data on dN/dy and dN/dp_T as well as ratios d/p and d̅/p̅ for heavy-ion collisions from AGS to top RHIC energies.

- A detailed analysis reveals that **stable clusters are formed**:
  - shortly after elastic and inelastic collisions have ceased
  - behind the front of the expanding energetic hadrons
  - since the ‘fire’ is not at the same place as the ‘ice’, cluster can survive

- PHQMD and UrQMD give very **similar coalescence and MST distributions of deuterons**.

- Shape of y-and p_T- distributions depends on a production mechanism → possibility to distinguish between production mechanisms experimentally!
Thank you for your attention!
Thanks to the Organisers!

https://phqmd.gitlab.io/
Hypernuclei production at $\sqrt{s_{NN}} = 3.0$ and $4.9$ GeV

S. Glässel et al., PRC 105 (2022) 1, 014908

Assumption for nucleon-hyperon potential: $V_{NL} = 2/3 V_{NN}$

=> trend of the experimental STAR* & $p_T$-spectra at $\sqrt{s_{NN}} = 3$ is produced well

=> yields are slightly overpredicted

*Yue-Hang Leung: First results of H3L & H4L ($dN/dy$, $c_T$, $v_1$, $v_2$) from 3 GeV Au+Au collisions with the STAR detector (CPOD2021)