Cluster and hyper-cluster production in HICs with PHQMD

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Motivation
Exploring the QCD-phase-diagram with clusters as experimental observables.
Understanding the production of clusters in relativistic heavy-ion collisions:
How can weakly bound clusters survive in the hot and dense environment of a HICs?

Challenge
Modeling the time evolution of cluster formation and the origin of their production.
PHQMD: dynamical evolution of HIC & cluster formation

PHQMD: J. Aichelin et al., PRC 101 (2020) 044905 & S. Gläßel et al., PRC 105, (2022) 014908

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| Interactions of hadrons  
Propagation of mesons  
QGP-phase | Propagation of baryons | Cluster identification |

Relativistic considerations

**off-shell** generalized transport equations based on *Kadanoff-Baym* equations

Dynamical Quasi Particle Model
quark / gluon spectral function $\rho_q(p, \omega)$:

mean-field potentials

Correlations between baryons

**n-body transport approach**

propagation of Gaussian wave functions $\psi_i$

QMD wave function for N particles $\psi_N = \prod_{i=1}^{N} \psi_i$

**Skyrme potential**

$$\langle V_{Skyrme}(\mathbf{r}_i, t) \rangle = \alpha \left( \frac{\rho_{int}(\mathbf{r}_i, t)}{\rho_0} \right) + \beta \left( \frac{\rho_{int}(\mathbf{r}_1, t)}{\rho_0} \right)$$

interaction density $\rho_{int}(\mathbf{r}_i, t)$

$\Rightarrow$ formation of clusters due to potential interactions

Minimum Spanning Tree

1. Two baryons are bound if $|r_i - r_j| < 4.0$ fm
2. Baryon is bound to cluster if bound with at least one baryon of cluster
PHQMD-simulations and experimental data (AGS & SPS)

E864 data: Au-Pb 0-10 % 10.6 AGeV

NA49 data: Pb-Pb 0-10 % 40 AGeV

B2 = \left( \frac{E d^3N_{d}}{E_p \frac{d^3N_{pp}}{dp_T^3} |p_T=P_d/2} \right)^2

=> Experimental rapidity- & p_{T}-distributions for light nuclei are reproduced at E_{lab} = 10.6 AGeV & 40 AGeV.

=> Probability that baryons with p_{T}/A form a cluster with size A almost independent of p_{T} (only slight increase).


PHQMD-simulations and experimental data (RHIC)

STAR data: Au-Au 7.7–200 GeV 0-10 % - light nuclei

=> $p_T$-distributions for deuterons are reproduced for $\sqrt{s} = 7.7 - 200$ GeV.


STAR data: Au-Au 3 GeV 0-10 % - hypernuclei

=> Trend of experimental STAR* $^3\Lambda$H & $^4\Lambda$H $p_T$-spectra is well produced.

=> Yields are slightly overpredicted.

=> Simple hyperon-nucleon interaction in PHQMD ($= 2/3$ of the nucleon-nucleon interaction)

When & where are clusters formed?

freeze-out time of baryon (last collision)

formation time of stable clusters

transverse distance to fireball center

$P(t)$

$P(A)$

$dN/dr_T$

$\Rightarrow$ Collisions of baryons essentially over after $t = 40 \text{ fm}/c$

$\Rightarrow$ Clusters formed shortly after collisions have ceased

$\Rightarrow$ Clusters formed behind the front of expanding energetic hadrons

Since the ‘fire’ is not at the same place as the ‘ice’, clusters can survive.