

Cluster formation near midrapidity can the mechanism be identified experimentally?

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&

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The ,holy grail' of heavy-ion physics:

The phase diagram of QCD







Experimental observables: ... Clusters and (anti-) hypernuclei

- EMD: Ch. Hartnack
- projectile/target spectators heavy cluster formation
- midrapidity → light clusters -

! Hyperons are created in participant zone

(Anti-) hypernuclei production:

- at mid-rapidity by coalescence of Λ with nucleons during expansion
- at projectile/target rapidity by rescattering/absorption of Λ by spectators

High energy HIC:

,Ice in a fire' puzzle: how the weakly bound objects can be formed and survive in a hot enviroment ?!



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Modeling of cluster and hypernuclei formation

Existing models for cluster formation:

- □ statistical model:
 - assumption of thermal equilibrium

□ coalescence model:

- determination of clusters at a freeze-out time by coalescence radii in coordinate and momentum space

don't provide information on the dynamical origin of cluster formation study of the state of the stat

A. Andronic et al., PLB 697, 203 (2011)

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 modeling of cluster formation based on interactions:
- via potential interaction 'potential' mechanism
- -- by scattering 'kinetic' mechanism



PHOMD



PHQMD



PHQMD: a unified n-body microscopic transport approach for the description of heavy-ion collisions and dynamical cluster formation from low to ultra-relativistic energies <u>Realization:</u> combined model PHQMD = (PHSD & QMD) & (MST/SACA)





Generalized Ritz variational principle:

$$\int_{t_1}^{t_2} dt < \psi(t) | i \frac{d}{dt} - H | \psi(t) \rangle = 0.$$

Assume that $\psi(t) = \prod_{i=1}^{N} \psi(\mathbf{r}_i, \mathbf{r}_{i0}, \mathbf{p}_{i0}, t)$ for N particles

Equations-of-motion (EoM) for $\psi(\mathbf{r}_i, \mathbf{r}_{i0}, \mathbf{p}_{i0}, t)$ - Gaussian centers in coordinate and momentum space:

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$$\dot{r_{i0}} = \frac{\partial \langle H \rangle}{\partial p_{i0}} \qquad \dot{p_{i0}} = -\frac{\partial \langle H \rangle}{\partial r_{i0}}$$

The expectation value of the Hamiltonian:

$$\langle H \rangle = \langle T \rangle + \langle V \rangle = \sum_{i} (\sqrt{p_{i0}^2 + m^2} - m) + \sum_{i} \langle V_{Skyrme}(\mathbf{r_{i0}}, t) \rangle$$

EoS for infinite matter at rest

$$\langle V_{Skyrme}(\mathbf{r_{i0}},t)\rangle = \alpha \left(\frac{\rho_{int}(\mathbf{r_{i0}},t)}{\rho_0}\right) + \beta \left(\frac{\rho_{int}(\mathbf{r_{i0}},t)}{\rho_0}\right)^{\gamma} -$$

modifed interaction density (relativistic extension):

$$\rho_{int}(\mathbf{r_{i0}},t) \rightarrow C \sum_{j} (\frac{4}{\pi L})^{3/2} e^{-\frac{4}{L} (\mathbf{r_{i0}^{T}}(t) - \mathbf{r_{j0}^{T}}(t))^{2}} \times e^{-\frac{4\gamma_{cm}^{2}}{L} (\mathbf{r_{i0}^{L}}(t) - \mathbf{r_{j0}^{L}}(t))^{2}},$$



Highlights: PHQMD ,bulk' dynamics from SIS to RHIC



PHQMD provides a good description of hadronic 'bulk' observables from SIS to RHIC energies

Mechanisms for cluster production in PHQMD: I. potential interactions (MST) & II. kinetic reactions



I. Cluster recognition: Minimum Spanning Tree (MST)

R. K. Puri, J. Aichelin, J.Comp. Phys. 162 (2000) 245-266

The Minimum Spanning Tree (MST) is a cluster recognition method applicable for the (asymptotic) final states where coordinate space correlations may only survive for bound states.

The MST algorithm searches for accumulations of particles in coordinate space:

1. Two particles are 'bound' if their distance in the cluster rest frame fulfills

 $|\overrightarrow{r_i} - \overrightarrow{r_j}| \leq 4 \text{ fm}$

2. Particle is bound to a cluster if it binds with at least one particle of the cluster.

* Remark:

inclusion of an additional momentum cut (coalescence) leads to small changes: particles with large relative momentum are mostly not at the same position (V. Kireyeu, Phys.Rev.C 103 (2021) 5)

MST + extra condition: E_B<0 negative binding energy for identified clusters





Cluster production in HICs



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The PHQMD comparison with recent STAR fixed target p_T distribution of p, d, t, ³He, ⁴He from Au+Au central collisions at $\sqrt{s} = 3$ GeV



→ Good description of cluster production



The PHQMD comparison with recent STAR fixed target p_T distribution of ${}^{3}H_{\Lambda}$, ${}^{4}H_{\Lambda}$ from Au+Au central collisions at $\sqrt{s} = 3 \text{ GeV}$ STAR: Phys. Rev. Lett. 128, 202301 (2022)

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



→ Reasonable description of hypernuclei production at $\sqrt{s} = 3$ GeV

PHQMD: S. Gläßel et al., Phys. Rev. C 105 (2022) 1



II. Deuteron production by hadronic reactions

"Kinetic mechanism"

- 1) hadronic inelastic reactions NN $\leftrightarrow d\pi$, π NN $\leftrightarrow d\pi$, NNN $\leftrightarrow dN$
- 2) hadronic elastic π +d, N+d reactions

u Hadronic reactions for d+ π and d+N scattering have very large cross sections $\sigma_{peak} \approx 200$ mb



□ the rates for the inverse processes pNN →pd, NNN→dN in hadronic matter are large due to the time-reversal symmetry

* Kinetic production by inverse reaction N + p + n → N + d first studied in HICs at E_{Lab} ~ 1 AGeV by P.J. Siemens, J. Kapusta PRL 43 (1979) 1486

Models for deuteron production by hadronic reactions



Collision Integral: covariant rate formalism

• Collision rate for hadron "i" is the number of reactions in the covariant volume d⁴x = dt*dV

$$\frac{dN_{coll}[3+4+5\to 1(d)+2]}{dtdV} = \int \left(\prod_{k=3}^{5} \frac{d^{3}p_{k}}{(2\pi)^{3}2E_{k}} f_{k}(x,p_{k})\right) \times \qquad \text{W. Cassing NPA 700 (2002) 618}$$

$$\int \frac{d^{3}p_{1}}{(2\pi)^{3}2E_{1}} \int \frac{d^{3}p_{2}}{(2\pi)^{3}2E_{2}} \frac{W_{3,2}(p_{3},p_{4},p_{5};p_{1},p_{2})(2\pi)^{4} \,\delta(p_{1}+p_{2}-p_{3}-p_{4}-p_{5})}{\text{use transition ampliture: } W(\sqrt{s}) + \text{detailed balance}}$$

• With test particle ansatz the transition rate for 3→2 reactions:



• Numerically tested in "static" box: PHQMD provides a good agreement with analytic solutions from rate equations and with SMASH for the same selection of reactions

Deutron production by $3 \rightarrow 2$ reaction in the PHQMD



1) RHIC BES energy vs = 7.7 GeV:

- Hierarchy due to large π abundance π +N+N \rightarrow π +d >> N+p+n \rightarrow N+d
- Inclusion of all isospin channels enhances deuteron yield ~ 50%.
- p_T slope is not affected



2) GSI SIS energy Vs < 3GeV :

- Baryon dominated matter
- Enhancement due to inclusion of isospin π +N+N channels is negligible

Modelling finite-size effects in kinetic mechanism

How to account for the quantum nature of deuteron, i.e. for

- 1) the finite-size of *d* in coordinate space (*d* is not a point-like particle) for in-medium d production
- 2) the momentum correlations of *p* and *n* inside *d*

Realization:

1) 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:

$$|\vec{r}(i)^* - \vec{r}(d)^*| < R_d$$

- Strong reduction of d production
- p_T slope is not affected by excluded volume condition







Same spirit as AMPT [K.-J. Sun, R. Wang, C.-M. Ko et al., 2106.12742]



Strong reduction of d production by projection on DWF $|\phi_d(p)|^2$

Kinetic vs. potential deuteron production

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)

PHOMD



• Good description of mid-rapidity NA49 data [PRC 94 (2016) 04490699]

G. Coci et al., Phys.Rev.C 108 (2023) 1, 014902

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Kinetic vs. potential deuteron production

Total d = Kinetic mechanism with finite-size effects + MST (with stabilization) identification of d



• Good description of mid-rapidity STAR data [PRC 99, (2019)]

Kinetic vs. potential deuteron production



PHQMD provides a good description of STAR data

□ The potential mechanism is dominant for d production at all energies!

Cluster formation near midrapidity - can the mechanism be identified experimentally?

3 mechanisms: coalescence at kinetic freeze-out, kinetic, potential deuteron productions



Observables, which are sensitive to the deuteron production mechanism: the rapidity distribution has a different form while the transverse momentum distribution has a different slope at low p_T V. Kireyeu et al., 2304.12019



When are the A=2 clusters formed?

- The normalized distribution of the freeze-out time of baryons (nucleons and hyperons) which are finally observed at mid-rapidity |y|<0.5</p>
- The conditional probability P(A) that the nucleons, which are finally observed in A=2 clusters at time 135 fm/c, were at time t the members of A=1 (free nucleons), A=2 or A=3 clusters



Stable clusters (observed at 135 fm/c) are formed shortly after the dynamical freeze-out



Comparison of the coalescence and MST for d



V. Kireyeu, J. Steinheimer, M. Bleicher, J. Aichelin, E.B., Phys. Rev. C 105 (2022) 044909



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

combined model PHQMD = (PHSD & QMD) & (MST | SACA)

- 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 $\overline{d}/\overline{p}$ 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

Coalescence and MST give very similar deuteron distributions within the PHQMD and UrQMD transport approaches