EPJ Web of Conferences **296**, 12003 (2024) https://doi.org/10.1051/epjconf/202429612003
*Quark Matter 2023*

# Mechanisms for cluster production in heavy-ion collisions near midrapidity

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**Abstract.** The formation of weakly bound clusters and hypernuclei in the hot and dense environment at midrapidity is a surprising phenomenon observed experimentally in heavy-ion collisions, spanning from low SIS to ultra-relativistic LHC energies. This occurrence, often referred to as the 'ice in a fire' puzzle, has prompted the exploration of three distinct approaches to elucidate cluster formation: the potential mechanism, involving cluster formation throughout the entire heavy-ion collision via potential interactions between nucleons; the kinetic mechanism, entailing deuteron production through catalytic hadronic reactions; and coalescence at kinetic freeze-out. In this context, we discuss the observables sensitive to the mechanism of cluster production, utilizing a microscopic transport Parton-Hadron-Quantum Molecular (PHQMD) approach.

## 1 Introduction

The study of light baryonic clusters in the central rapidity region of ultra-relativistic heavy-ion collisions is presently a subject of considerable interest, attracting substantial research efforts from both theoretical and experimental perspectives. A key scientific inquiry arising in recent years is centered on understanding the mechanisms involved in the production and survival of these loosely bound objects within the intense heat and density of the central collision region. Additionally, a central methodological challenge lies in determining how to effectively identify and calculate these clusters in dynamic simulations of heavy-ion reactions.

## 2 Mechanisms for cluster production

To model the dynamic formation of clusters, three commonly employed approaches are utilized:

[*]Speaker

*1. Coalescence approach* [1–4]:
The coalescence mechanism is predominantly applied to the production of deuterons and light clusters. This method posits that all clusters are formed during kinetic freeze-out, occurring after the hadronic expansion phase. According to this approach, if, at freeze-out time, a neighboring nucleon with the appropriate charge is found within the coalescence radius in both coordinate and momentum space, these two nucleons are deemed to form a deuteron or part of a light cluster. The coalescence radii are determined through fitting experimental multiplicities.
*2. Potential mechanism* [5–8]:
The potential interaction among nucleons in the hadronic phase gives rise to bound clusters of various sizes, and their multiplicity is contingent upon the specifics of the expansion of the hot interaction zone and its composition. Modeling this dynamic cluster formation via potential nucleon interactions involves propagating the n-body phase space density, a task accomplished in approaches like Quantum Molecular Dynamics (QMD). The identification of clusters at different stages of the system's dynamical evolution is carried out using the advanced Minimum Spanning Tree (aMST) procedure, i.e. MST followed by the stabilization procedure, detailed in Ref. [6]. It is crucial to emphasize that MST serves as a cluster recognition method rather than a 'cluster-building' mechanism, given that the QMD transport approach propagates baryons rather than pre-formed clusters.
*3. Kinetic mechanism* [9–12]:
Light clusters, such as deuterons, can be generated through inelastic reactions involving hadrons, such as $NN\pi \to d\pi$ and $NNN \to dN$, where a pion or a nucleon acts as a 'catalyst' during the hadronic phase of heavy-ion collisions. They are called 'kinetic' deuterons. In the initial application of this 'kinetic' mechanism within the transport model SMASH, the three-body $3 \to 2$ reactions were substituted by two two-body collisions incorporating an intermediate fictitious dibaryon resonance $d^*$ [9]. Subsequently, in a more recent development, the three-body entrance channel has been directly modeled by employing detailed balance with respect to experimentally measured inverse $\pi d$ and $Nd$ scattering [11].

In our recent publication [12], we extended the investigation presented in Ref. [11] by incorporating all isospin channels for pion-induced reactions within the microscopic Parton-Hadron-Quantum Molecular Dynamics approach (PHQMD) [6]. Additionally, we consider finite-size effects of deuterons, reflecting their quantum origin. Two distinct approaches are employed for this purpose: I) an excluded-volume condition that hinders the formation of deuterons in the presence of surrounding hadrons, and II) a projection of the relative momentum of the $NN$-pairs onto the deuteron wave function. In our study [12], we demonstrate that the inclusion of each of these finite-size effects leads to a substantial but comparable suppression of deuterons at mid-rapidity. When both effects are applied simultaneously, the deuteron yield experiences an additional factor of two suppression. Within the 'kinetic' approach, the production and destruction of deuterons can occur throughout the entire hadronic expansion of the hot interaction zone. However, computational results indicate that only clusters produced at later stages tend to persist. These observations are consolidated and discussed in detail in Ref. [13].

In Refs. [4, 14], we conducted a comparative analysis of the coalescence and potential mechanisms for cluster formation. These mechanisms were integrated into the PHQMD and UrQMD transport approaches to ensure model-independent results. Our findings reveal that both clustering methods yield similar behaviour for deuteron observables, including rapidity and transverse momentum distributions, within both the UrQMD and PHQMD frameworks. However, as detailed in Ref. [13], our investigation uncovered a noteworthy distinction: only around 20% of the MST deuterons were identified as deuterons in the coalescence approach.

In other words, there is a difference in the content of clusters identified by these two methods. In this proceedings we briefly recall the results reported in Refs. [12, 13].

## 3 Results

The rapidity distribution $dN/dy$ of kinetic and potential deuterons in central Pb+Pb collisions (impact parameter interval $b = 0 - 5$ fm) are shown in the upper row of Fig. 1. The PHQMD calculations [12] include modeling of finite-size effects by excluded-volume and momentum projection of proton and neutron to the wave function of a deuteron. The rows collect results for the energy range of the SPS facility; $E_{Lab} = 20, 40, 158$ GeV per nucleon. The dots are the experimental data from the NA49 collaboration [15]. The lines correspond to the PHQMD results for different production mechanizm of deuterons: kinetic $d$ (thin red), potential $d$ from aMST, i.e. MST followed by the stabilization procedure (dashed green), total $d$ (thick solid blue). One can see that the shape of the rapidity spectra from kinetic and potential deuterons are different when going out of mid-rapidity. As shown in Ref. [13] the shape of $y-$ spectra from the coalescence model depends on the collision energy and shows a more flat distribution. This opens the possibility to distinguish the production mechanisms by measuring the rapidity distributions close to midrapidity.

The transverse momentum distributions $d^2N/dp_T dy$ of deuterons at mid-rapidity are shown in the lower row of Fig. 1 taken in correspondence with the NA49 experimental data [15]. It is seen that the slopes of kinetic deuterons are harder then the one of poten-

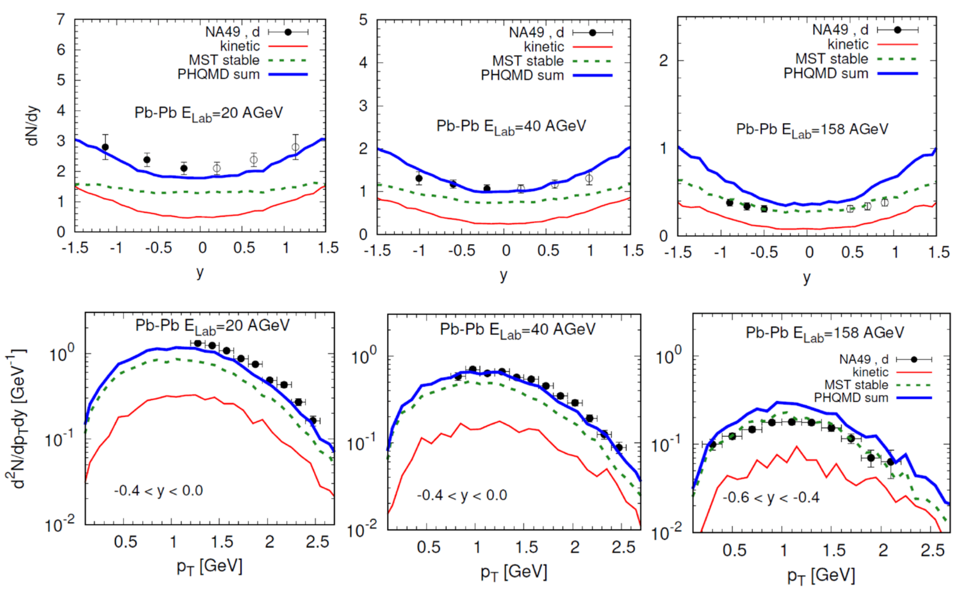


**Figure 1.** The rapidity distributions $dN/dy$ (upper row) and the transverse momentum distributions $dN/dp_T dy$ for fixed rapidity intervals (lower row) of deuterons for Pb+Pb central collisions at $E_{Lab}$ = 20, 40, 158 AGeV. The full dots are the experimental data from the NA49 collaboration [15] (the empty dots are mirrored around mid-rapidity). The lines correspond to the PHQMD results for different production mechanizm of deuterons: kinetic $d$ (thin red), potential $d$ from aMST, i.e. MST followed by the stabilization procedure (dashed green), total $d$ (thick solid blue).

tial deuterons, while - as shown in Ref. [13] - the slope of deuterons formed by coalescence are softer.

## 4 Conclusions

We explored three distinct approaches to deuteron production—coalescence, 'potential,' and 'kinetic' mechanisms—each proposed to elucidate the finite cluster yield observed at midrapidity in ultra-relativistic heavy-ion collisions. Our analysis reveals observable features that are sensitive to the deuteron production mechanism: the rapidity distribution exhibits a distinct form, and the transverse momentum distribution shows a different slope at low $p_T$. These discernible differences are significant enough to be measurable, providing an opportunity to distinguish between the various mechanisms for deuteron production when comparing these results with experimental data.

Identifying the mechanism not only contributes to the understanding of how deuterons are produced, but also sheds light on their survival in the hot and dense medium generated during heavy-ion collisions, thereby addressing the intriguing 'ice in the fire' puzzle.

*Acknowledgements:* The authors acknowledge the partial support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), by the GSI-IN2P3 agreement under contract number 13-70 as well as by the European Union's Horizon 2020 research and innovation program under grant agreement STRONG–2020 – No 824093.

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