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

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The formation of weakly bound clusters and hypernuclei in the hot and dense environment at midrapidity is one of the surprising phenomena observed experimentally in heavy-ion collisions from low SIS to ultra-relativistic LHC energies. This is also known as the 'ice in a fire' puzzle. Three approaches have been advanced to describe the formation of clusters: cluster formation during the entire heavy-ion collision by potential interactions between nucleons ('potential mechanism') and deuteron production by catalytic hadronic reactions ('kinetic mechanism') as well as by coalescence at kinetic freeze-out.

We present here results from PHQMD [1,2], a novel microscopic n-body transport model based on the QMD propagation of the baryonic degrees of freedom with density dependent 2-body potential interactions. The clusters, formed via 'potential' mechanism, are recognized by the Minimum Spanning Tree (MST) algorithm which is identifying bound clusters by correlations of baryons in coordinate space.
The PHQMD approach allows for studying in the same framework the two above mentioned mechanisms, to investigate how and when clusters are formed and finally for comparing the results with present data from GSI to RHIC energies.

We report on our recent findings, in particular that:

- The clusters produced via coalescence and potential mechanisms are created after the fast hadrons are escaped from the reaction zone, i.e. clusters remain in transverse direction closer to the center of the heavy-ion collision than free nucleons. Thus, since the 'fire' is not at the same place as the 'ice', cluster can survive which explains the ice in the fire puzzle. Our PHQMD results for deuteron production by potential mechanism agree quantitatively with results of UrQMD for coalescence deuterons, thus, this finding doesn't depend on the transport model involved.
- For the 'kinetic' deuterons the PHQMD results agrees with those from SMASH - if one limits the catalytic hadronic reaction channels to those realized in SMASH, however, accounting for all isospin channels of the various $\pi NN \leftrightarrow \pi d$, $NNN \leftrightarrow Nd$ reactions leads to an enhanced production of deuterons.
- On the other hand, we find that considering the quantum nature of the deuteron – by taking into account the finite size properties of the deuteron by means of an excluded volume in coordinate space and by the projection onto the deuteron wave function in momentum space – reduces substantially the kinetic deuteron production in a dense medium as encountered in heavy-ion collisions. This makes the 'kinetic' mechanism sub-dominant compared to the deuteron formation by potential interactions between nucleons.
- The sum of kinetic deuterons and that produced in by potential interactions reproduces well the experimental data from SIS to RHIC energies
- The coalescence deuterons and potential deuterons have only about 20\% of the nucleons in common. This leads to a different rapidity distribution and to a different p_T-distribution at low p_T. This difference can be used to identify experimentally the production mechanism which is realized in nature.
- Heavier clusters like t, ^3He and ^4He as well has hypernuclei are also well reproduced by the potential mechanism

Some of the presented result have been published in Refs. [3,4,5].

[1] J. Aichelin, E. Bratkovskaya, A. Le Fevre, V. Kireyeu, V. Kolesnikov, Y. Leifels, V. Voronyuk and G. Coci, Phys. Rev. C 101 (2020) 044905, [arXiv:1907.03860 [nucl-th]].
[2] S. Glässel, V. Kireyeu, V. Voronyuk, J. Aichelin, C. Blume, E. Bratkovskaya, G. Coci, V. Kolesnikov and M. Winn, Phys.Rev. C 105 (2022) 1, [arXiv:2106.14839 [nucl-th]].
[3] V. Kireyeu, J. Steinheimer, J. Aichelin, M. Bleicher and E. Bratkovskaya, Phys. Rev. C 105 (2022) 044909, [arXiv:2201.13374 [nucl-th]].
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[5] V. Kireyeu, G. Coci, S. Glässel, J. Aichelin, C. Blume and E. Bratkovskaya, [arXiv:2304.12019 [nucl-th]].

Category

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