Clusters as a probe of the equation-of-state of strongly interacting matter

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Abstract. We investigate the influence of the equation-of-state (EoS) of strongly interacting matter created in heavy-ion collisions on the light cluster and hypernuclei production within the Parton-Hadron-Quantum-Molecular Dynamics (PHQMD) microscopic transport approach. In earlier PHQMD calculations, nucleon interactions were modeled using a static, density-dependent potential corresponding to the soft and hard equation-of-state. In this study, we incorporate a momentum-dependent potential for the baryon-baryon interaction, derived from the soft EoS. We study the influence of momentum dependent potential on light cluster production.

1 Introduction

The study of light baryonic clusters in the central rapidity region of ultra-relativistic heavy-ion collisions has garnered significant theoretical and experimental interest. A key focus is understanding the mechanisms behind the production and survival of these loosely bound objects in the extreme heat and density of the collision zone. Additionally, a major challenge lies in accurately identifying and calculating these clusters in dynamical simulations of heavy-ion reactions. At low beam energies, the cluster production is directly linked to the nucleon dynamics, which is highly sensitive to baryon-baryon potential interactions related to nuclear matter equation-of-state (cf. a review and refs. therein [1]). One of the key question is related to study of the sensitivity of different observables to the equation-of-state of nuclear matter, which is a subject of this study.

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2 Cluster production within the PHQMD

The Parton-Hadron-Quantum-Molecular Dynamics is a microscopic n-body transport model based on the QMD propagation of the baryonic degrees of freedom, where the clusters are formed via 'potential' and "kinetic" mechanisms [2–7].

The interaction between nucleons in the hadronic phase leads to the formation of bound clusters of varying sizes, with their multiplicity depending on the expansion dynamics and composition of the hot interaction zone. Modeling this cluster formation through nucleon interactions involves propagating the n-body phase space density, a process used in methods like Quantum Molecular Dynamics (QMD). Cluster identification throughout the system's evolution is achieved using the advanced Minimum Spanning Tree (aMST) method, which combines MST with a stabilization procedure, as outlined in Ref. [3]. It is important to note that MST is a recognition method for clusters, not a mechanism for their formation, as QMD propagates baryons rather than pre-formed clusters.

The identification of clusters at different stages of the system's dynamical evolution is carried out using the advanced Minimum Spanning Tree 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.

Additionally, 'kinetic' mechanisms for deuteron production are incorporated by catalytic hadronic reactions accounting for all isospin channels of the various $\pi NN \leftrightarrow \pi d$, $NNN \leftrightarrow Nd$ reactions which enhances deuteron production. It also considers the quantum nature of the deuteron by means of its finite size modelled by the finite-size excluded volume effect in coordinate space and a projection of the relative momentum of the interacting pair of nucleons on the deuteron wave-function in momentum space, leading to a strong reduction of deuteron production, especially at target/projectile rapidities.

In Refs. [8–11], we conducted a comparative analysis of the coalescence, potential and kinetic mechanisms for cluster formation within the PHQMD model and compared this also to the coalescence of UrQMD models. We have found that there are observables, which are sensitive to the deuteron production mechanism: the rapidity distribution has a different form and the transverse momentum distribution has a different slope at low p_T. These differences are large enough to be measurable and will allow, therefore, for discriminating between the different mechanisms for deuteron production when confronting these results with data [11].

In the previous PHQMD calculations we employed a static interaction between nucleons in terms of density dependent potential, which corresponds to the soft and hard EoS. Here have incorporated the momentum dependent potential for the baryon-baryon interaction which is evaluated from the soft EoS. The parameters of momentum dependent potential are fitted to the "optical" potential (i.e. Schrödinger equivalent potential U_{SEP}), extracted from elastic scattering data in pA reactions [12, 13]. The potential grows up to the total momentum of proton $p \sim 1.5$ GeV$/c$ and then decreases. The extended publication of the influence of momentum dependent potential is in preparation now. Here we report our preliminary results from this study.

3 Results

We have studied the influence of equation-of-state realized via different baryon-baryon potential: static soft (S), static hard (H) and soft momentum dependent (SM) potentials, on different observables such as rapidity distributions, transverse momentum spectra of protons and light clusters as well as collective observables - the flow coefficients v_1 and v_2 as a function of rapidity and p_T transverse momentum for different energies - from SIS to low BES RHIC.

In Figure 1 we show the PHQMD results for the transverse momentum p_T-spectra of protons, deuterons, tritons, ^{3}He, ^{4}He for Au+Au 0-10% central collisions at $\sqrt{s_{NN}}$ = 3 GeV for different rapidity bins calculated with 3 different EoS: soft EoS -indicated as dashed lines, hard EoS - presented by the dotted lines and soft with momentum dependent potential - shown by solid lines. While at the low SIS energies the p_T-spectra show a pronounced splitting depending on the particular EoS chosen, at low BES-RHIC energies of $\sqrt{s_{NN}}$ = 3 GeV the difference between static hard potential and momentum dependent soft potential are relatively small due to the fact that the potential decreases with increasing proton energy. A comparison of the PHQMD results to the STAR data [14] shows that the soft momentum dependent EoS provides a better description of STAR data. However, the hard static potential spectra are only slightly softer then those calculated with the momentum dependent soft EoS.

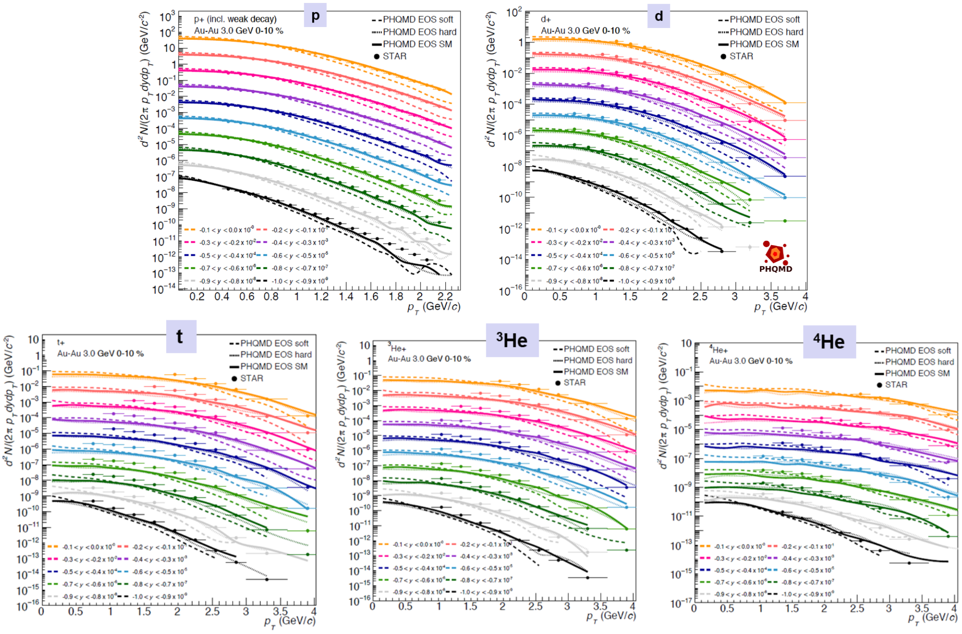

Figure 1. The PHQMD results for the transverse momentum p_T-spectra of protons, deuterons, tritons, ^{3}He, ^{4}He for Au+Au 0-10% central collisions at $\sqrt{s_{NN}}$ = 3 GeV for different rapidity bins (scaled with 10^n factors for distinguishing lines) calculated with 3 different EoS: soft EoS - indicated as dashed lines, hard EoS - presented by the dotted lines and soft with momentum dependent potential - shown by solid lines, in comparison to the STAR data [14].

4 Conclusions

In this contribution we have discussed the influence of EoS on the cluster observables. The comparison of the PHQMD results to the HADES and STAR data show a strong sensitivity of the transverse momentum spectra and the flow coefficient v_1 and especially elliptic flow coefficient v_2 on momentum dependence of the potential at SIS energies while this sensitivity decreases with increasing energies due to the decrease of potential as demonstrated in the example figure presented in this contribution. The extended study within the PHQMD on this issue is following up.

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