Prospects for the study of the strangeness production within the PHQMD model

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Abstract. Strangeness and hypernuclei production in heavy-ion collisions is presently under active experimental and theoretical investigation and is of particular interest for the experiments at the new acceleration complex NICA (Nuclotron-based Ion Collider fAcility) which is under construction at the Joint Institute for Nuclear Research (Dubna, Russia). We study the production of (hyper)nuclei in the NICA energy range using a novel n-body dynamical transport approach called Parton-Hadron-Quantum-Molecular Dynamics (PHQMD).

1. Introduction

Modern science makes it possible to produce and study rare exotic types of matter in the laboratory: high energy experiments at LHC (CERN) are able to investigate the soup of the first microsecond after the Big Bang, while future lower energy experiments at NICA (Dubna) and FAIR (Darmstadt) are designed to study dense matter similar to the matter which can be observed in neutron star mergers [1]. To produce this new type of the matter in the laboratory normal matter has to be heated and compressed. One of the possible ways to do it is to use heavy ion collisions.

In ultra-relativistic heavy ion collisions a quark–gluon plasma (QGP) is formed. When it expands hadronization processes occur together with the formation of clusters. Above the strangeness threshold energy also the production of hypernuclei can take place in the mid-rapidity region if Λ hyperons coalesce with nucleons during the expansion or by the absorption of Λ hyperons penetrated to the target/projectile spectator region due to re-scattering by spectators.

There are a number of statistical and coalescence models which describe the formation of clusters. The disadvantage of these models is that they assume that clusters are produced at a given time point. Therefore they do not provide any information on the dynamics of clusters formation. In order to understand the microscopic origin of clusters formation one needs a realistic model for the dynamical time evolution of the heavy ion collisions and a dynamical modeling of cluster formation.

Since clusters are weekly bound objects, their formation is sensitive to nucleon dynamics, that means that initial and final nucleon correlations should be kept and one needs realistic nucleon-nucleon interactions in transport models. Quantum-molecular dynamics (QMD) [2] as a n-body approach allows to keep such correlations, while in mean-field (MF) based models these correlations are smeared out.

2. Parton-Hadron-Quantum-Molecular-Dynamics model

The Parton-Hadron-Quantum-Molecular-Dynamics (PHQMD) [3] is a n-body dynamical transport approach which is designed to provide a microscopic description of light and heavy clusters and hypernuclei formation in addition to the general particle production in heavy-ion reactions at relativistic energies. PHQMD extends the Parton-Hadron-String Dynamics (PHSD) [4] transport approach implementing the following properties:
1) The propagation of baryons is based on the QMD dynamics, realized by density dependent 2-body potential interactions which allow to propagate the n-body phase-space correlations between baryons.
2) The description of the mesons and the QGP dynamics as well as the collision integral were taken from the PHSD model. The original PHSD mean-field propagation for baryons within the parallel ensemble method is kept as an option. This allows to investigate the differences between the QMD and MF approaches on "bulk" observables.
3) The identification of the clusters can be done within two methods: the minimum spanning tree (MST) procedure or by the Simulated Annealing Clusterization Algorithm (SACA) [5].
Besides that, the nuclear matter equation of state (EoS) can be changed from the more attractive ("soft" EoS) to the more repulsive ("hard" EoS).

Figures1-2 show the $m_T - m_0$ spectra of protons, π^+, K^+, K^- and $\Lambda + \Sigma^0$, for central Au+Au collisions at beam energies of 4, 6, 8 and 10.7 AGeV, calculated in PHQMD with a "hard" and a "soft" EoS. The PHQMD results are compared with those from PHSD as well as with the AGS experimental data [6, 7, 8, 9, 10, 11, 12]. Models predictions are in a good agreement with the experimental data. The transverse mass spectra of protons show a sensitivity to the EoS at all energies. A "hard" EoS increases the slope of the spectra at large m_T and lowers the yield at low m_T as compared to a "soft" EoS. PHQMD results for the m_T spectra with "soft" EoS are in a good agreement with the PHSD spectra (with default "soft" EoS in the PHSD 4.0), this can give an indication that QMD and MF dynamics gives similar results with similar EoS. Contrary to the proton m_T spectra, the spectra of newly produced hadrons indicate only a very mild dependence on the nucleon potential.

In the Minimum Spanning Tree procedure only the coordinate space information is used to identify clusters. This method can find clusters only when nucleons and groups of nucleons are well separated in coordinate space at the end of the reaction. Two nucleons are considered as "bound" if the distance between them is less or equal to $r_0 = 4.0$ fm. A particle is bound to a cluster if it is bound with at least one particle of the cluster. Inclusion of additional momentum cuts lead to small changes: particles with large relative momentum are mostly not at the same position at the end of the reaction.

The Simulated Annealing Cluster Algorithm was developed on to overcome the limitation that clusters can be found only at the end of the reaction. SACA allows to study the clusterization pattern shortly after the time after which the two nuclei passed each other when the different final state clusters still overlap in coordinate space. SACA takes the positions and momenta of all nucleons at time t, combines them in all possible ways into all kinds of clusters or leaves them as single nucleons neglecting the interaction among clusters. Then for each possible configuration of clusters and free nucleons the total binding energy is calculated and that configuration which has the highest binding energy is chosen. This procedure allows to identify clusters early during the reaction and allows therefore for the study of the dynamics and of the origin of clusters.

Figure 3 shows the PHQMD results for the scaled rapidity distributions for the $Z = 1$ clusters and unbound protons in comparison with FOPI experimental data for central Au+Au collisions

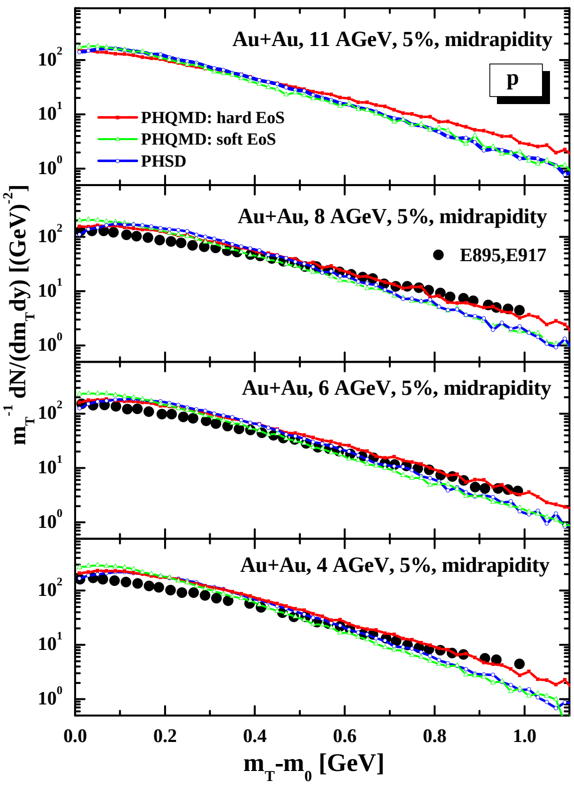


Figure 1. (Color online) The transverse mass spectra of protons at midrapidity for 5% central $Au + Au$ collisions at 4, 6, 8, 10.7 A.GeV (plots from lower to upper). The experimental data are from [6]. Solid red lines with open squares refer to the PHQMD results with a "hard" EoS, the green lines with open triangles to the PHQMD results with a "soft" EoS, the blue lines with open circles show the PHSD results.

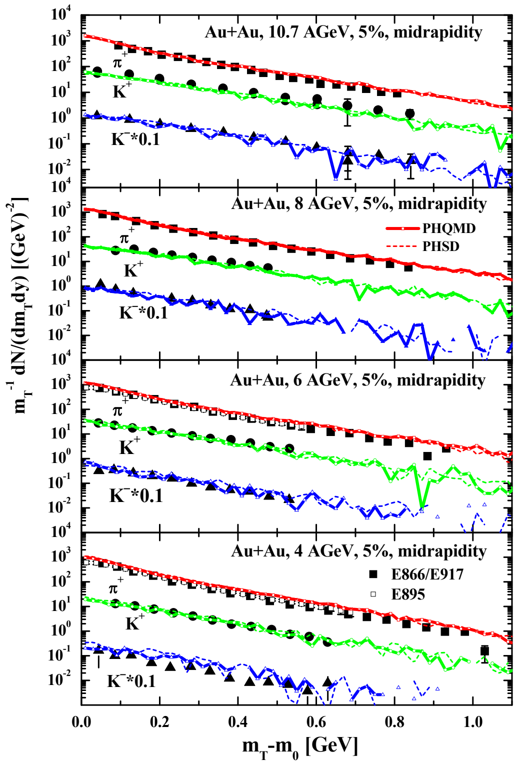


Figure 2. (Color online) The transverse mass spectra of π^+, K^+, K^- and $\Lambda + \Sigma^0$ at midrapidity for 5% central $Au + Au$ collisions at 4, 6, 8, 10.7 AGeV (from lower to upper) in comparison to the experimental data from Refs. [7]– [12]. Solid lines with open symbols refer to PHQMD results with a "hard" EoS, the dashed line to PHSD results.

at 1.5 AGeV [13]. The scaled rapidity distribution of $Z = 1$ clusters is in agreement with the data as well as the rapidity distribution of free protons, also shown in figure 3. Presently SACA is not so efficient as MST in the description of the light clusters at midrapidity and, correspondingly, underestimates the number of nucleons which are bound in clusters. Therefore, for further analysis of light clusters and hypernuclei the MST algorithm will be used.

Figure 4 shows the distribution of $Z = 1$, $Z = 2$ particles, heavier clusters ($Z > 2$), all Λ's, light ($A \leq 4$) and heavy ($A > 4$) hypernuclei identified by the MST algorithm as a function of the rapidity for Au+Au collisions at 10 AGeV. An enhancement of the yield of $Z = 1$ particles, Λ's and heavier clusters is observed close to the projectile and target rapidity and an almost constant distribution for $Z = 1$ particles is visible in between. The production of hyperons increases towards midrapidity. Only a small fraction of the hyperons ends up in light hypernuclei at midrapidity, while at the spectators region where more of the produced hyperons end up as part of a larger hyper-cluster.

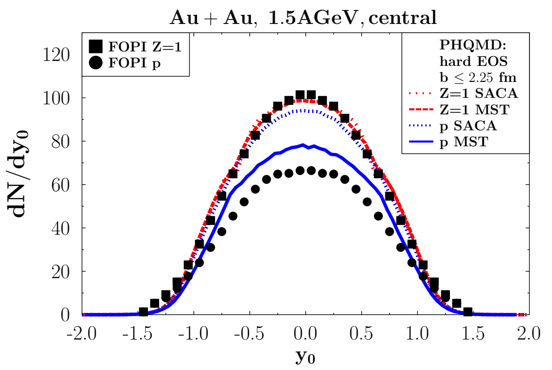


Figure 3. Scaled experimental rapidity distribution, $y_0 = y/y_{proj}$, of all, bound and unbound, protons ($Z = 1$) – solid squares, and of unbound protons - solid dots, observed by the FOPI collaboration in central Au+Au collisions at 1.5 AGeV [13] in comparison to the PHQMD results: clusters have been identified by the MST (red dotted line) or by the SACA (red dashed line); the rapidity distributions of free protons after subtracting the protons bound in clusters identified by MST (blue solid line) or by SACA (blue short dotted line)

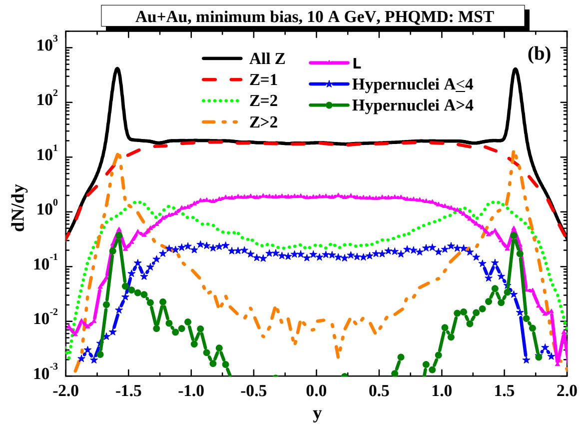


Figure 4. (Color online) The PHQMD results (MST, "hard" EoS) for the rapidity distributions of all charges (black solid line), $Z = 1$ particles (red dashed line), $Z = 2$ clusters (green dotted line), $Z > 2$ (orange dot-dot-dashed line), all bound and unbound Λ's (magenta line with triangles) as well as of light hypernuclei with $A \leq 4$ (blue line with stars) and heavy hypernuclei with $A > 4$ (green line with dots) as a function of the rapidity for central Au+Au collisions at 10 AGeV.

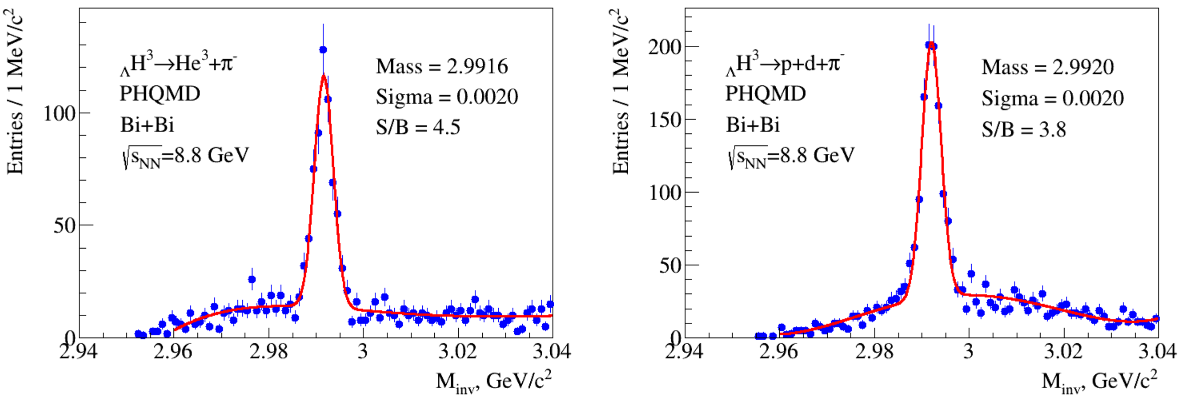
3. Multi-Purpose Detector

The NICA facility is under active construction at the Joint Institute for Nuclear Research in Dubna. It will provide a variety of ion beams from protons to bismuth nuclei in the $\sqrt{s_{NN}}$ = 4-11 GeV energy range. The main physics goal of the NICA heavy-ion program is the experimental study of the QCD phase diagram in the highest baryon density region. In order to meet all of the NICA project's goals, the Multi-Purpose Detector (MPD) [14] is designed as a large acceptance spectrometer which should be able to provide the precise tracking, particle identification (PID), reconstruction of the event plane and the collision centrality. All detector subsystems are located inside a homogeneous magnetic field of 0.5 T. The MPD time-projection chamber (TPC) is used for charged particle reconstruction and particle identification by measuring the specific energy loss. The wide dynamic range of TPC measurements also allows for the identification of such light nuclei as deuterons, tritons, and helium isotopes. Charged hadrons in the range of momenta up to 3 GeV/c can be identified using a time-of-flight (TOF) system. A more detailed description of all detector components can be found in [14].

4. Reconstruction of hypernuclei in the MPD detector

Hypernuclei analysis was performed using the PHQMD model with the MST cluster recognition algorithm. All the produced particles from the model were passed through the detector material using the GEANT3 transport package. As the next step, the detector response simulation was performed together with the reconstruction procedure and realistic particle identification. The PID was achieved by using both the TPC ionization loss and time-of-flight measurements from the TOF subsystem. In order to reconstruct hypertritons, secondary vertices were reconstructed for identified (^{3}He, π^-) pairs by applying a set of additional topological and kinematic cuts.

The results on $^3_\Lambda H$ hypernuclei reconstruction are presented in figure 5: (a) shows the obtained invariant mass distributions for $^3_\Lambda H \rightarrow He^3 + \pi^-$ mode, (b) demonstrates the invariant mass distribution for the $^3_\Lambda H \rightarrow p + d + \pi^-$ mode. The results have been obtained for $1.5 \cdot 10^7$ min. bias $Bi + Bi$ collisions at the energy of $\sqrt{s_{NN}} = 9$ GeV. Blue dots represent the reconstructed data points, while the red curve is the sum of a polynomial used to evaluate the combinatorial background and a Gaussian function for the signal.



(a) (b)

Figure 5. Reconstructed invariant mass spectra of $^3_\Lambda H$: 2-prongs decay mode (a) and 3-prongs decay mode (b).

5. Conclusions

The MPD experiment at NICA is designed for the study of the less explored region of the QCD phase diagram. The MPD setup offers good opportunities for the study of the production of hypernuclei in heavy-ion collisions at NICA energies. The PHQMD model realized as a microscopic n-body transport approach for the description of heavy-ion dynamics and cluster formation may provide the theory for the hypernuclei formation process in the hot and dense matter.

6. Acknowledgments

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7. References

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