Production of nuclei in heavy-ion collisions at GeV energies

Nihal Buyukcizmeci [1]

[1]*Department of Physics, Science of Faculty, Selçuk University, Konya, Türkiye*

collaboration with A.S. Botvina, M. Bleicher

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INTRODUCTION

- Production of initial nucleons

  - The Ultra-relativistic Quantum Molecular Dynamics Model (UrQMD)[1,2]

  - The Dubna Cascade Model (DCM) [3]

- Clusterization of baryons and deexcitation

  the Statistical Multifragmentation Model (SMM) [4]

- Results for distributions of nuclei and hypernuclei and comparison with the STAR experimental data

- Conclusions

[1] N. Buyukcizmeci, T. Reichert, A. S. Botvina, and M. Bleicher, Phys. Rev. C **108**, 054904 (2023).

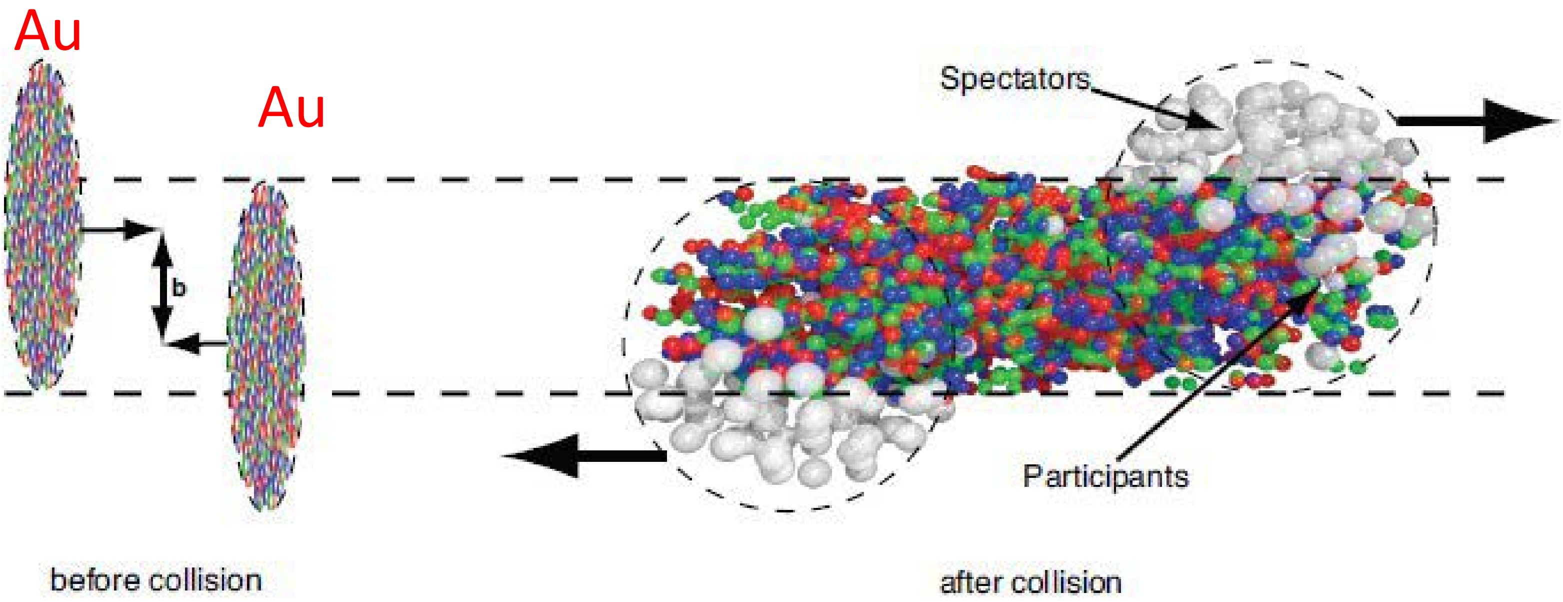
[2] Apiwit Kittiratpattana, Tom Reichert, Nihal Buyukcizmeci, Alexander Botvina, Ayut Limphirat, Christoph Herold, Jan Steinheimer, and Marcus Bleicher, Phys. Rev. C **109**, 044913 (April 2024)

[3] V. D. Toneev, K. K. Gudima, Nucl. Phys. A 400, 173 (1983).

[4] A. S. Botvina, N. Buyukcizmeci and M. Bleicher, Phys. Rev. C 106, 014607 (2022).

STAR exp.: Central Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV

[5] M. S. Abdallah et al., STAR Collaboration, Phys. Rev. Lett. 128, 202301 (2022)
[6] Hui Liu for STAR Collaboration, Acta Phys. Polon. B, Proc. Suppl. 16, 1–A148 (2023).



Hybrid approaches are successful for the description of dynamics

DCM+CB (primary hot nuclei) URQMD

DCM+SMM (final cold nuclei) URQMD+SMM

The Ultra-relativistic Quantum Molecular Dynamics Model (UrQMD)

- The UrQMD includes up to 70 baryonic species (including their antiparticles), as well as up to 40 different mesonic species, which participate in binary interactions. In the present calculations the hard Skyrme type equation of state is used which allows for the attraction between baryons.
- Conservation of the net-baryon number, net-electric-charge, and net-strangeness as well as the total energy and momentum are taken into account.
- The produced particles can be located at all rapidities, however, the considerable part is concentrated in the midrapidity region.
- At the time of t=20–40 fm/c the strong interactions leading to the new particle formation are practically stopped (such as saturation). In that time-moment we consider the relative coordinate positions and velocities of the produced baryons.
- We select the nuclear clusters according to the coordinates and velocities proximity, was suggested in Refs. [1,2,4], and we call it a clusterization of baryons (CB).

[7] M. Bleicher et al., J. Phys. G 25, 1859 (1999),
[8] S.A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998).

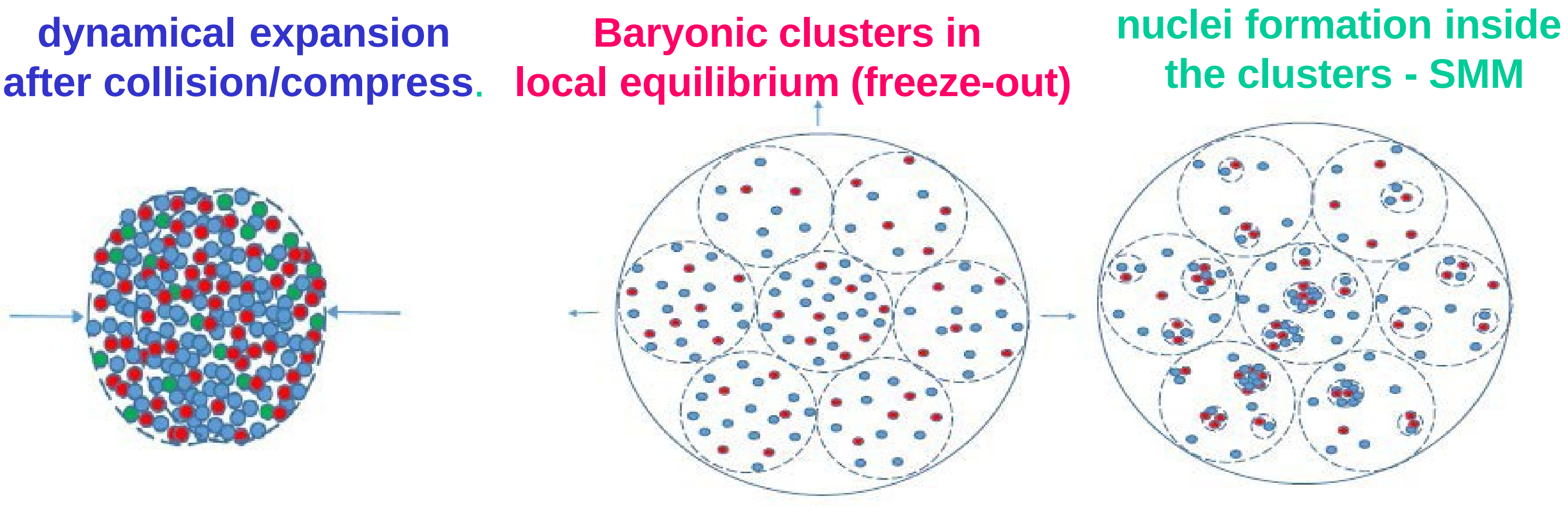
CENTRAL COLLISIONS

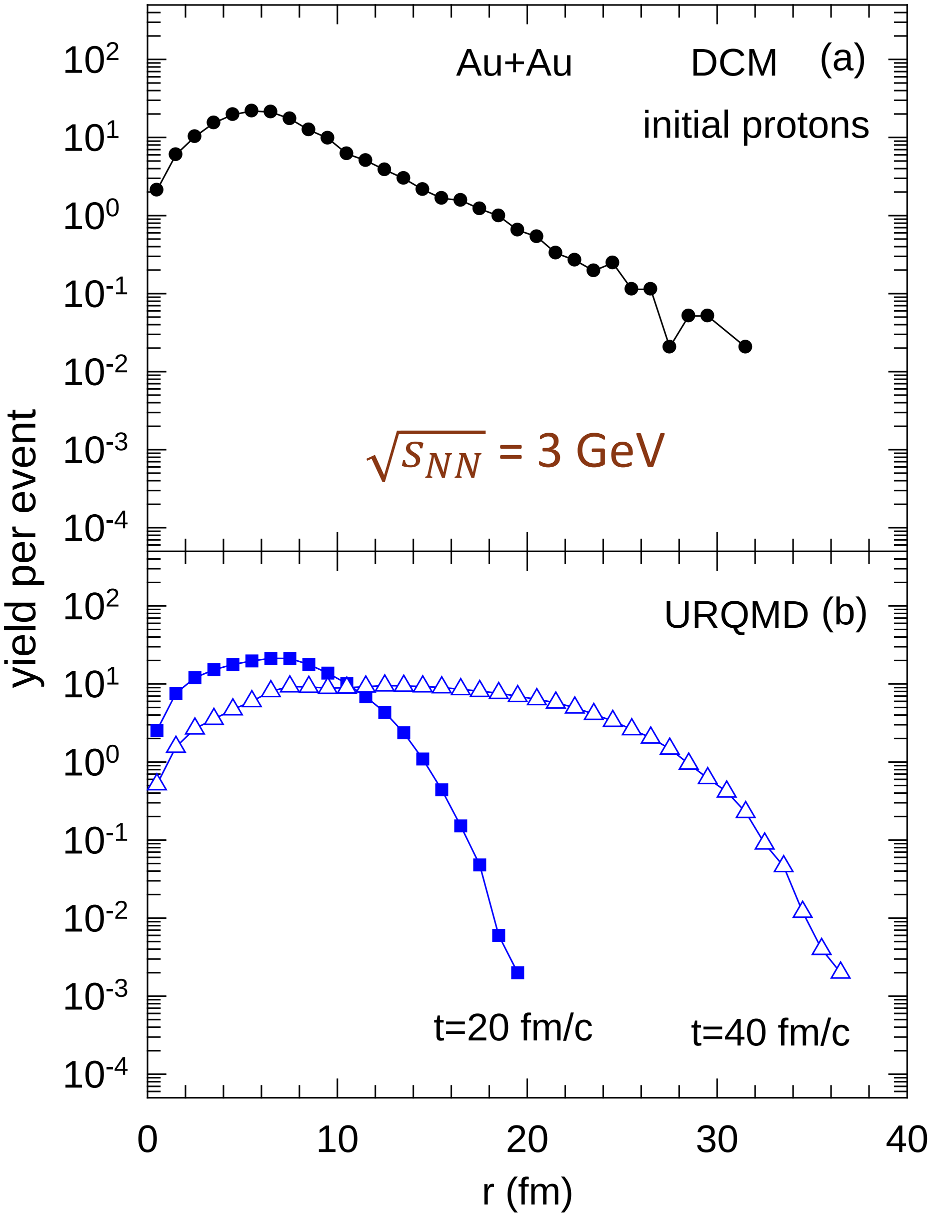
Nuclear system expands to low densities and passes the density around 0.1-0.3 of normal nuclear density, which corresponds to the freeze-out adopted in the statistical models. Baryons can still interact and form nuclei at this density. We divide the nuclear matter into clusters in local chemical equilibrium and apply SMM to describe the nucleation process in these clusters.

Baryons (both nucleons and hyperons) can produce a cluster with mass number A if their velocities relative to the center-of mass velocity of the cluster is less than vc.

$$|\vec{v}_i - \vec{v}_{cm}| < v_c \text{ for all } i = 1, \ldots, A, \text{ where } \vec{v}_{cm} = \frac{1}{E_A}\sum_{i=1}^{A} \vec{p}_i$$

The distance between the individual baryons and the center of mass of the clusters should be less than $2 \cdot A^{1/3}$ fm, so these baryons can still interact leading to the nuclei formation.



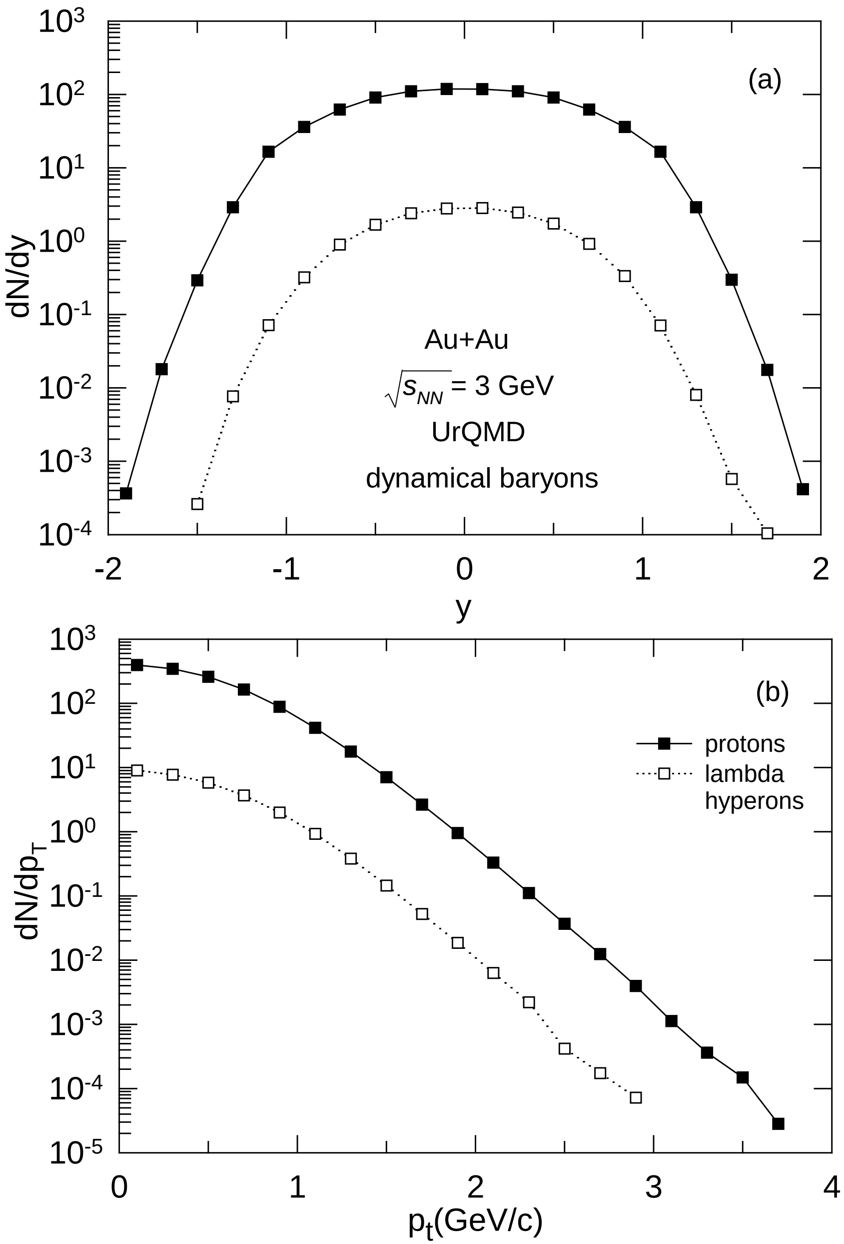


DISTRIBUTION OF INITIAL PROTONS ACCORDING TO THE CENTER OF COLLISION

Initial protons and Λ's

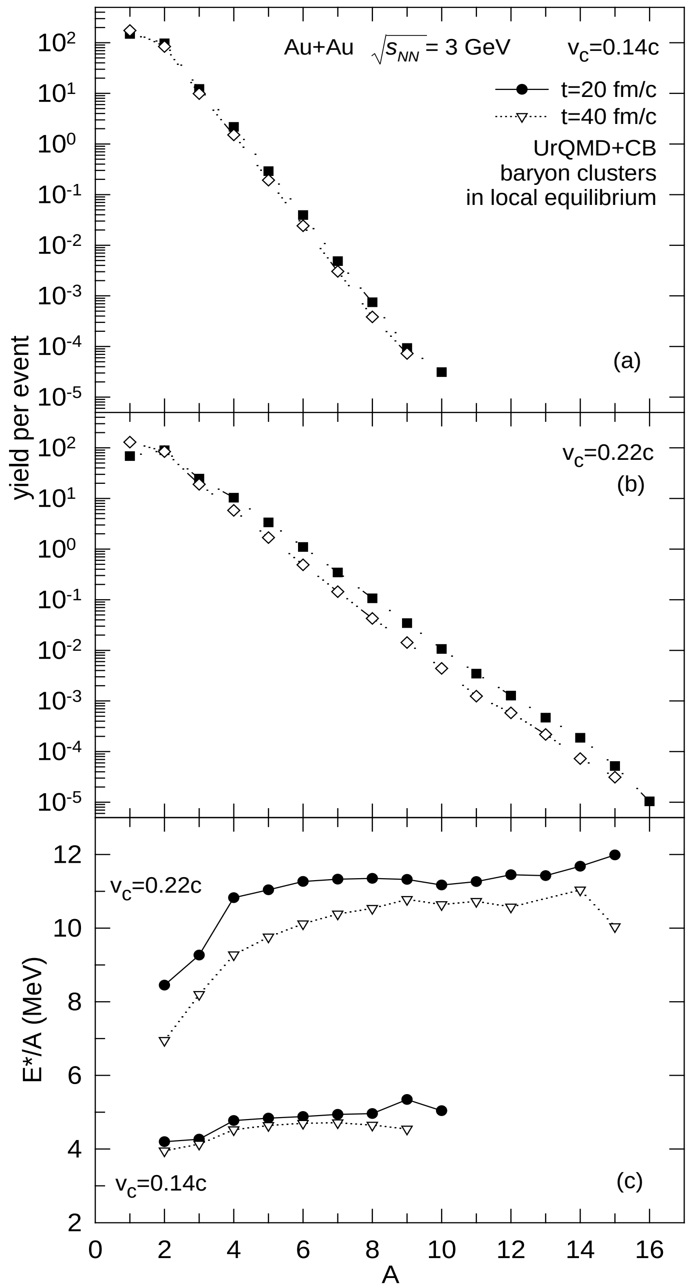
Total proton and Λ distributions after the UrQMD calculations of central Au+Au collisions at center-of-mass energy of $\sqrt{s_{NN}} = 3$ GeV. Top panel (a) rapidity distributions. Bottom panel (b) transverse momenta distributions, in the rapidity range |y|<0.5.

[1] N. Buyukcizmeci, T. Reichert, A. S. Botvina, and M.Bleicher, Phys. Rev. C **108**, 054904 (2023).



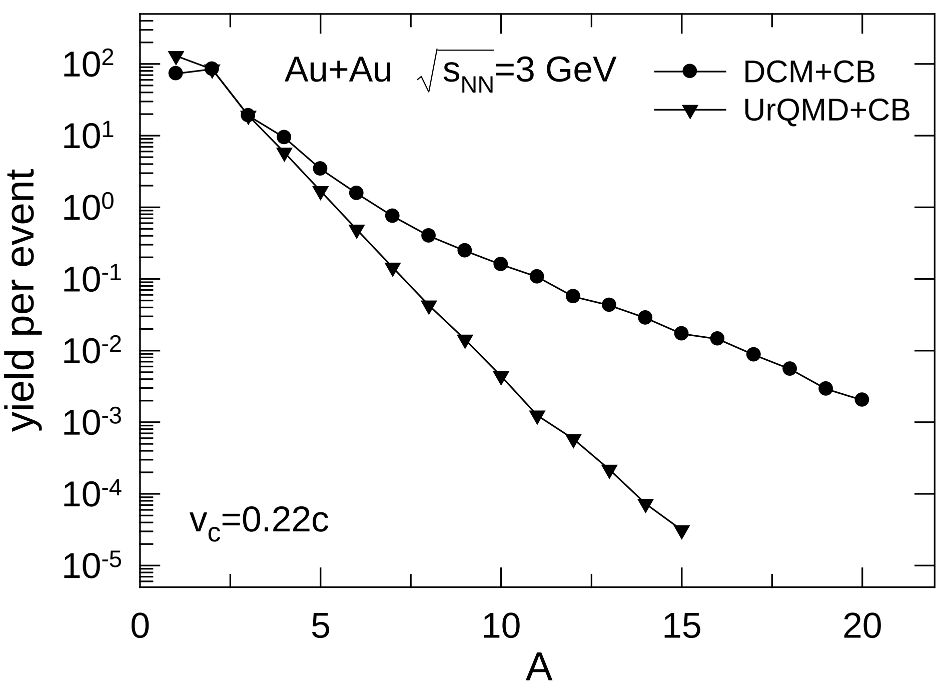
Yields of nuclei and hypernuclei and excitation energies

Figure 2: Calculated distributions of local nuclear clusters (per event) formed from dynamically produced baryons after UrQMD and the clusterization (CB) procedure by using the selection of the baryons with the velocity and coordinate proximity. Top panel (a) mass distributions of the cluster with the velocity parameter vc=0.14c. Middle panel (b) mass distributions of the cluster with the velocity parameter vc=0.22c. Bottom panel (c) average excitation energy of the clusters versus their mass number. The times for stopping the UrQMD calculations and vc parameters are shown in the panels.

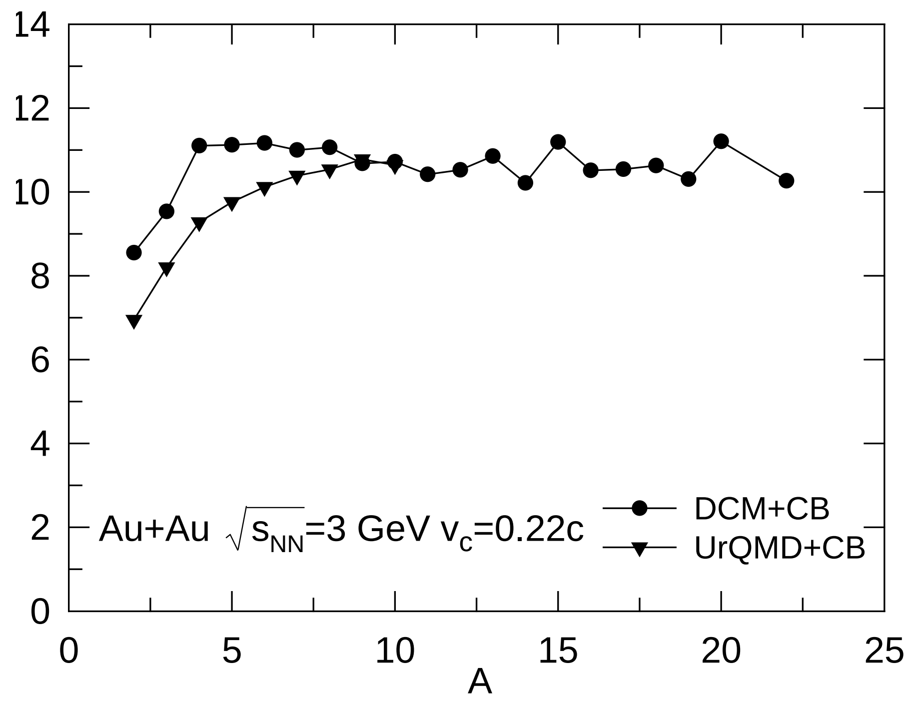


hot baryon clusters

Mass distributions



Excitation energies

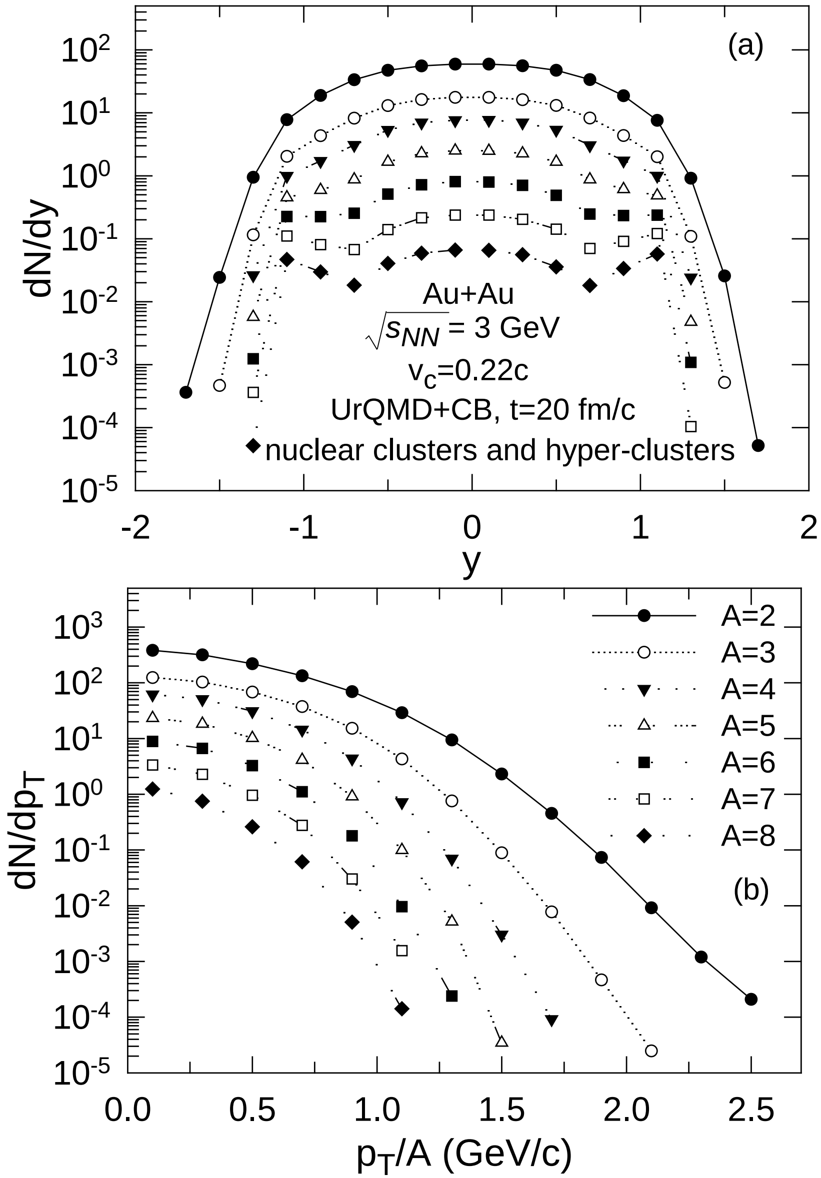


The calculations are performed with the UrQMD and DCM to generate baryons in central Au+Au collisions, $v_c = 0.22c$ is applied for the identification of hot clusters.

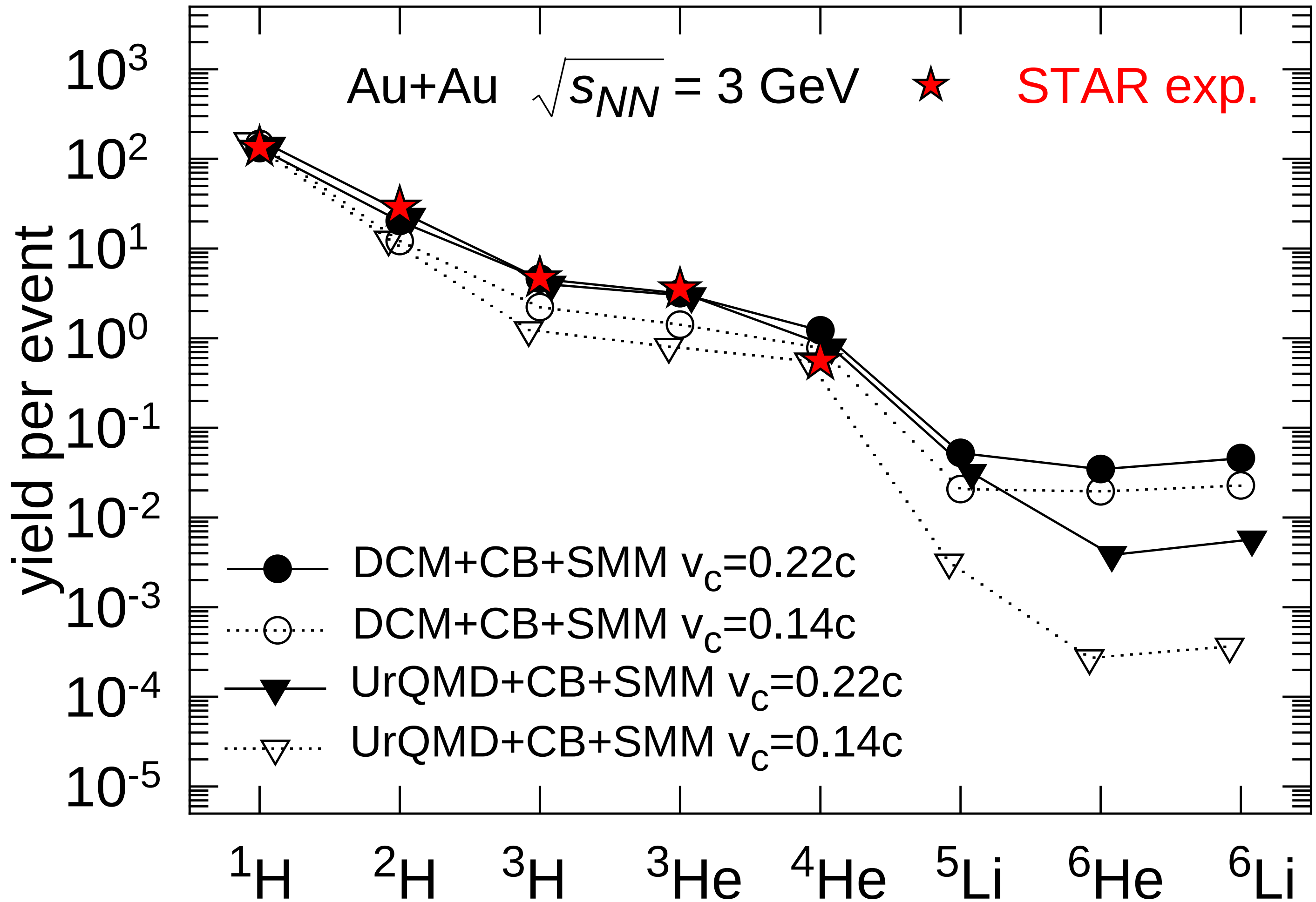
Light nuclei and hypernuclei: A=2-8

Figure 3: Rapidity (top panel (a)) and transverse momentum per nucleon (bottom panel (b)) Distributions of the excited baryon clusters, which have the mass numbers from A=2 to 8. Yields are per event.

N. Buyukcizmeci, T. Reichert, A. S. Botvina, and M.Bleicher, Phys. Rev. C **108**, 054904 (2023).

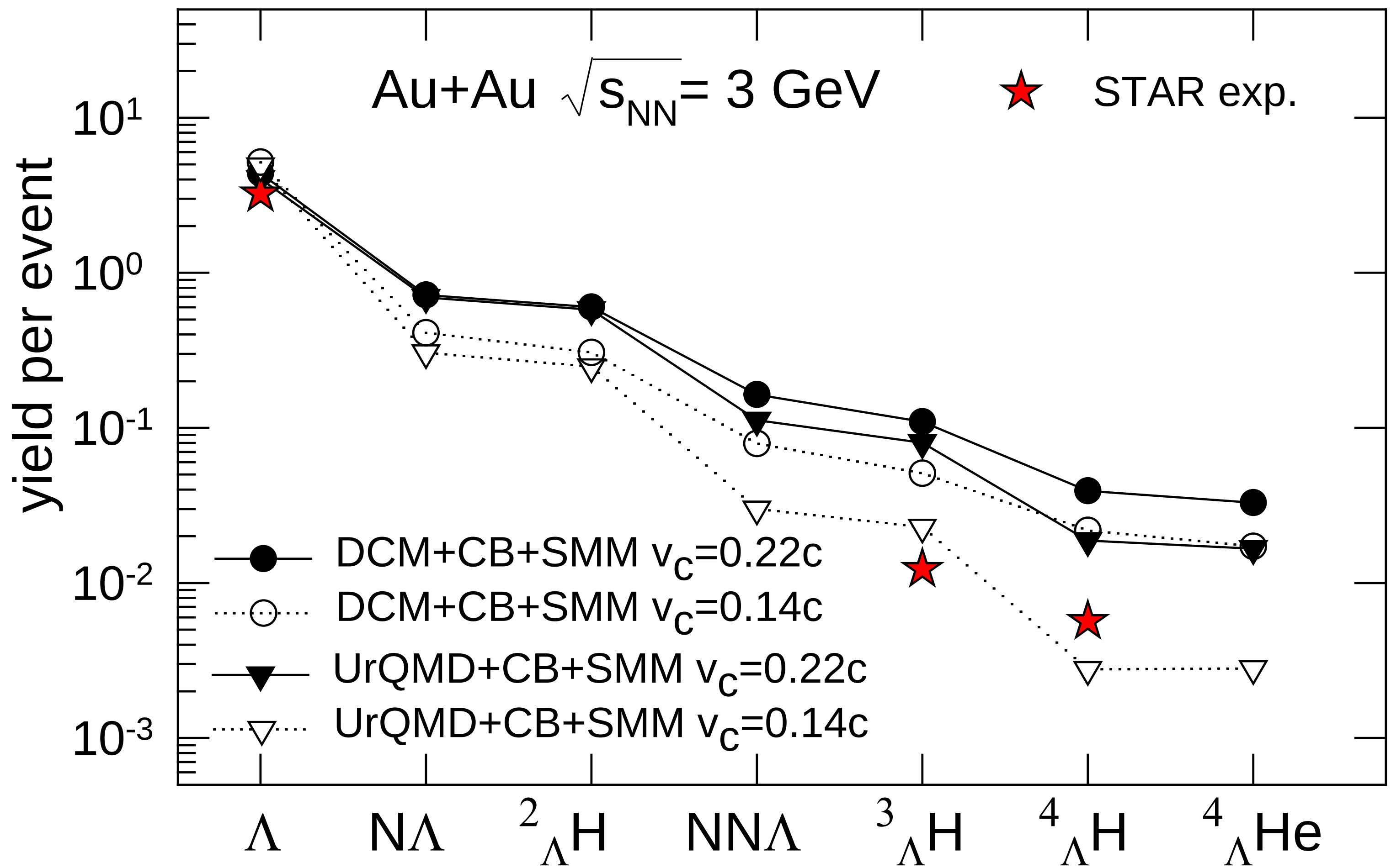


Comparison with the STAR data



N. Buyukcizmeci, Yu Lebed, A. S. Botvina, (2024), accepted to Physics of Particles and Nuclei Letters.

Comparison of light hypernuclei with the STAR data



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Signals from the STAR Exp.

$$^{5}_{\Lambda}\mathrm{He} \rightarrow \; ^{4}\mathrm{He}\ p\ \pi^-$$

FIAS Annual Report 2022

Future research will be possible to detect heavier hypernuclei!

Search for hypernuclei in the STAR experiment

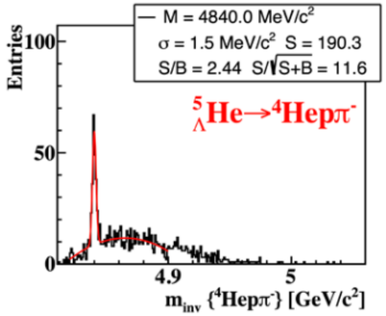
Hypernuclei search in the STAR experiment at Brookhaven National Laboratory (BNL) in the USA is an ongoing research effort aimed at studying the properties of nuclei that contain strange quarks.

The STAR experiment is a large-scale collaboration in heavy-ion physics that utilizes the Relativistic Heavy Ion Collider (RHIC) at BNL to study the properties of matter at extreme conditions, including the behavior of strange quarks in nuclei. The experiment uses high-energy collisions of heavy ions to create new forms of matter, including hypernuclei, which are then detected and analyzed. The study of hypernuclei provides valuable information on the behavior of strange quarks in the nuclei and can shed light on our understanding of the strong interaction, the force that holds the nucleus together.

In recent years, the STAR experiment has made significant contributions to the field of hypernuclear physics, including the observation of new hypernuclei and the measurement of their properties. The results of these studies have helped to improve our understanding of the strange quark sector and the behavior of baryons in extreme conditions. The study of hypernuclei continues to be an active area of research in the STAR experiment, and new developments and advancements are expected in the future.

Moreover, the study of hypernuclei also has potential implications for several other areas of physics, including the study of neutron stars, the properties of dense matter, and the behavior of strange quarks in a nuclear environment. In addition to the STAR experiment, there are several other ongoing efforts to study hypernuclei, both at accelerator facilities and through theoretical calculations. These efforts complement each other and provide a comprehensive understanding of the strange quark sector.

Recently, as part of the Beam Energy Scan (BES-II) research program in the STAR experiment, our FIAS group, together with scientists from the CBM (FAIR/GSI) and STAR (BNL) groups, using the CBM FLES reconstruction algorithms, has detected in real time 37916 Λ^3H, 37819 Λ^4H, 978 Λ^4He, and 190 Λ^5He hypernuclei. The detection of such a significant number of hypernuclei will allow us to study in detail the behavior of strange quarks in the hypernuclei.



In the STAR experiment within the Beam Energy Scan (BES-II, 2019-2021) research program, our FIAS group, together with scientists from the CBM (FAIR/GSI) and STAR (BNL) groups, using the CBM FLES reconstruction algorithms, has detected 190 Λ^5He hypernuclei at a significance level of 11.6, which means that the signal level exceeds the background fluctuations by a factor of 11.6.

Prof. Dr. Ivan Kisel

He works on data reconstruction in high-energy and heavy-ion experiments. His approach based on cellular automata allows to develop parallel algorithms for real-time physics analysis using HPC. He received his PhD in physics and mathematics from the Joint Institute for Nuclear Research (Dubna, 1994). Then he worked at the University of Heidelberg, where he gained his habilitation in physics, in 2009, and at the GSI Helmholtz Centre for Heavy Ion Research. Since 2012, he is a professor for software for HPC at the Goethe University and a fellow at FIAS.

Highlight

We detected 76.903 hypernuclei in real time in the STAR experiment (BNL, USA) using the FLES reconstruction algorithms of the CBM experiment (FAIR/GSI).

Projects at FIAS: 3

Staff

Artemiy Belousov
Akhil Mithran
Oddharak Tyagi
Robin Lakos
Gianna Zischka

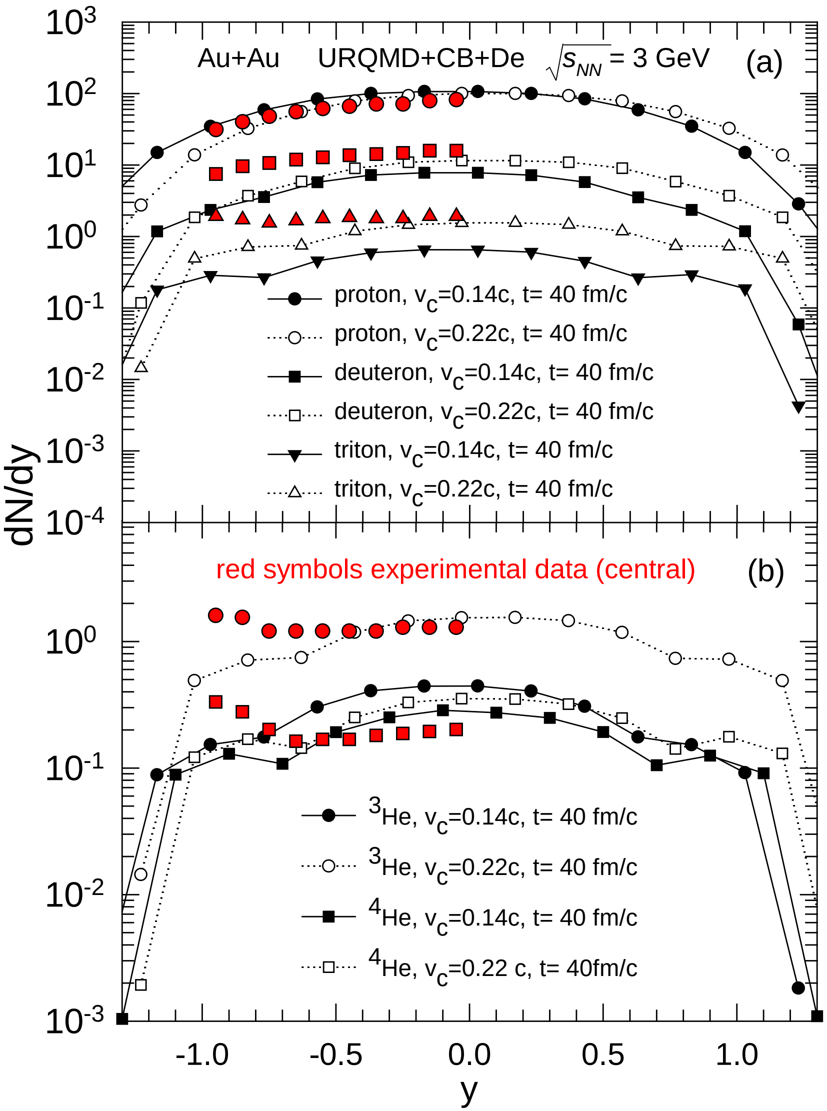
Collaborations

CBM
ALICE
STAR

Comparison with the STAR data for light nuclei

Comparison of the calculations of the rapidity distributions of normal nuclei produced in central collisions with STAR experimental data. (a) protons, deutrons, tritons. (b) ^{3}He, ^{4}He. The model parameters are indicated in the panels.

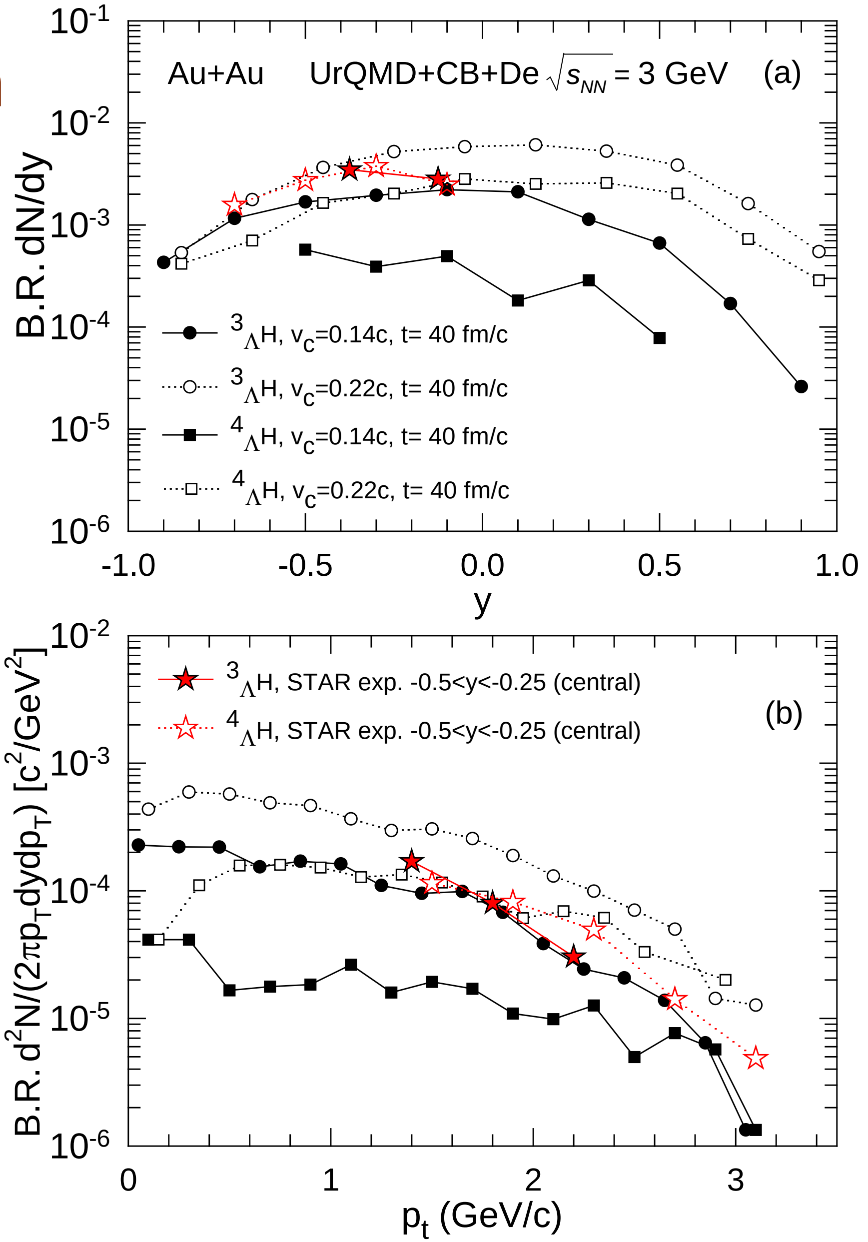
[1] N. Buyukcizmeci, T. Reichert, A. S. Botvina, and M. Bleicher, Phys. Rev. C **108**, 054904 (2023).



Comparison with the STAR data

$^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H

Figure 6: Comparison of the calculations of the rapidity (top panel (a)) and transverse momentum distributions (bottom panel (b)) of $^{3}_{\Lambda}$H, and $^{4}_{\Lambda}$H hypernuclei with STAR experimental data [9]. The model parameters are indicated in the panels.



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CONCLUSIONS

- It is shown that the (hyper)nuclei yields obtained in the STAR experiments can be successfully described by using the DCM+SMM and UrQMD+SMM hybrid models. We use the idea of local chemical equilibrium in the expanding nuclear matter.
- This agreement can be obtained when the parameters of hot nuclear matter in the clusters coincide with the parameters of finite nuclear systems extracted from multifragmentation studies.
- We predict many heavy (and exotic) nuclei and hypernuclei which detection would be crucial for better determination of the reaction mechanism and properties of hypermatter at subnuclear density.
- More experimental data needed (especially, which are related to the correlations of the produced particles and nuclei), and we hope it will be available soon, after the experiments at NICA (Dubna) and FAIR (Darmstadt).
- Thank you for your attention!

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