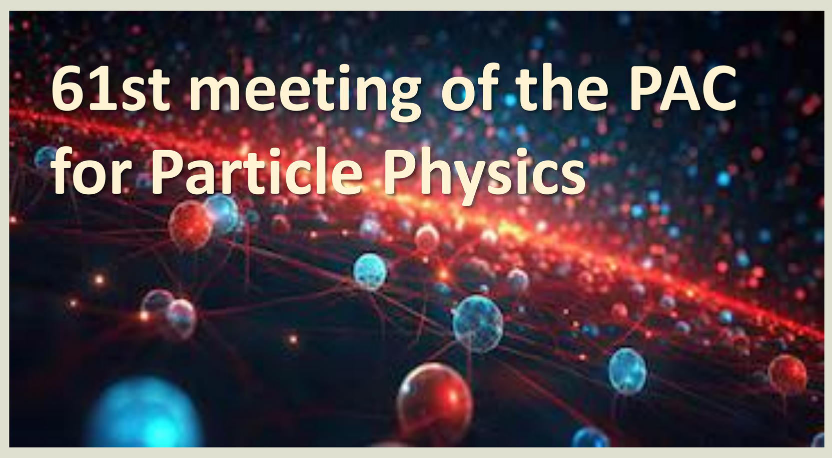
JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin Laboratory of High Energy Physics

Modelling of light (hyper)nuclei production in heavy-ion collisions at NICA energies based on generator THESEUS

Marina E. Kozhevnikova and Yuri B. Ivanov



INRTODUCTION

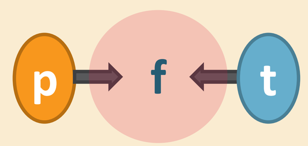
- Light-nuclei production is related to search for critical point in QCD phase diagram.
- Spinodal instability: abundant production of light nuclei due to density fluctuations in spinodal region.
- At moderately relativistic energies light nuclei give significant contribution to the total baryon charge of the system of colliding nuclei (≈30% in Au+Au collisions at the energy $\sqrt{s_{NN}} = 3$ GeV).
- Various 3D dynamical models describing light nuclei exist: with coalescence mechanism, microscopic dynamical approaches (SMASH, PHQMD).
- THESEUS (Three-fluid Hydrodynamics-based Event Simulator Extended by UrQMD (Ultrarelativistic Quantum Molecular Dynamics) final State interactions) generator uses **thermodynamical approach** for modelling of light (hyper)nuclei on the equal basis with hadrons. **No additional parameters are needed.**
- Main areas of research: study the light-(hyper)nuclei production at collision energies of the BES-RHIC, SPS, NICA and FAIR.

1 Model 3FD and generator THESEUS

The 3FD [1] simulates the early, nonequilibrium stage of the collision and describes it until the freeze-out.

- **baryon-rich fluids:** nucleons of the projectile (p) and the target (t) nuclei;
- **fireball (f) fluid:** newly produced particles which dominantly populate the midrapidity region during the evolution process.

Problems: no afterburner, application.



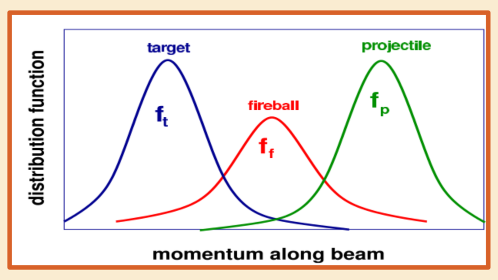
THESEUS [2] is based on the 3FD model, performs the procedure of particlization. The kinetic stage (or afterburning) is modeled by means of UrQMD, which describes hadronic rescatterings.

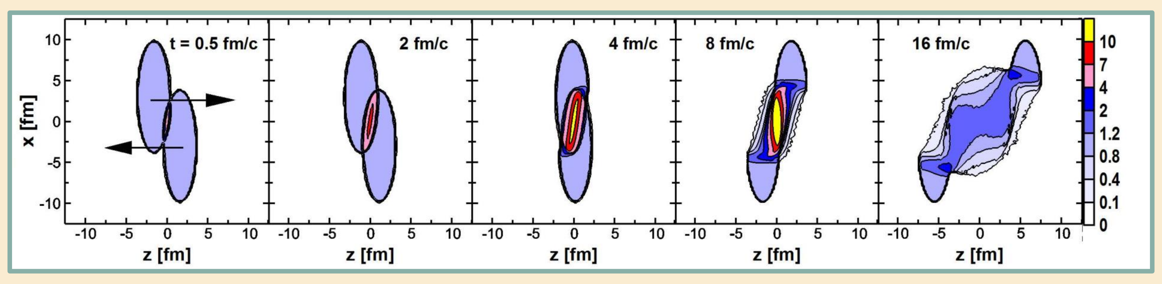
THESEUS = 3FD + Monte-Carlo hadron sampling + afterburner via UrQMD.

THESEUS uses 3FD output (T, μ_B, μ_S) to generate particles ($x, y, z, p_x, p_y, p_z, E, \ldots$) ;

It presents the output in terms of **a set of observed particles.**

It is suitable for application of experimental acceptance!





Hadronic EoS
only hadronic states (hadron gas), no phase transition (Mishustin, Russkikh, Satarov)

1PT EoS
hadronic states+QGP with 1st-order phase transition (Khvorostukhin, Skokov, Toneev, Redlich)

Crossover EoS
hadronic states + QGP with a smooth transition (crossover) between phases (Khvorostukhin, Skokov, Toneev, Redlich)

HYDRODYNAMICAL MODELLING OF NUCLEAR COLLISIONS

1. **Initial state & hydrodynamic evolution:** 3FD uses hydrodynamical equations with friction terms modelling of the interaction between fluids
2. **Particlization:** THESEUS allows to move from the description in terms of liquid to a kinetic description.
3. **Afterburner:** UrQMD (optionally) describes hadronic rescattering (or afterburning) processes.
4. **Detector response:** Experimental cuts can be easily applied

2 RESULTS

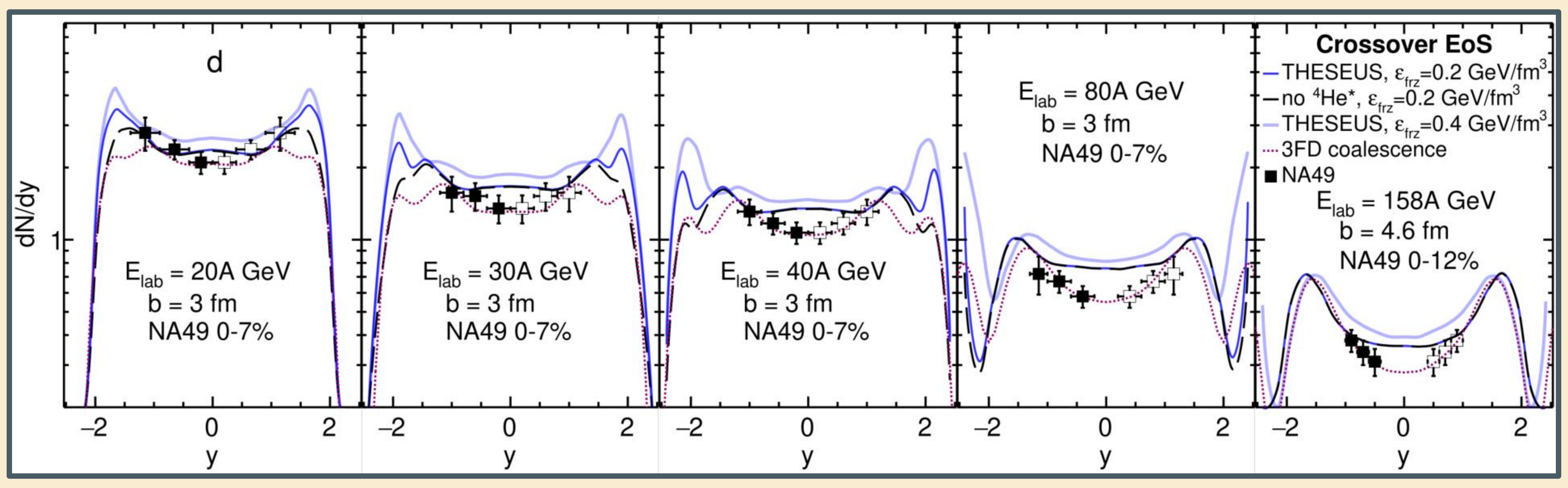


Fig.1: THESEUS and 3FD results [3] on rapidity distributions of deuterons in comparison with NA49 [4] data calculated for three different EoS and with late freeze-out ($\varepsilon_{frz} = 0.2$ GeV/fm^3). For comparison, the result with standard freeze-out ($\varepsilon_{frz} = 0.4$ GeV/fm^3) for crossover EoS is shown.

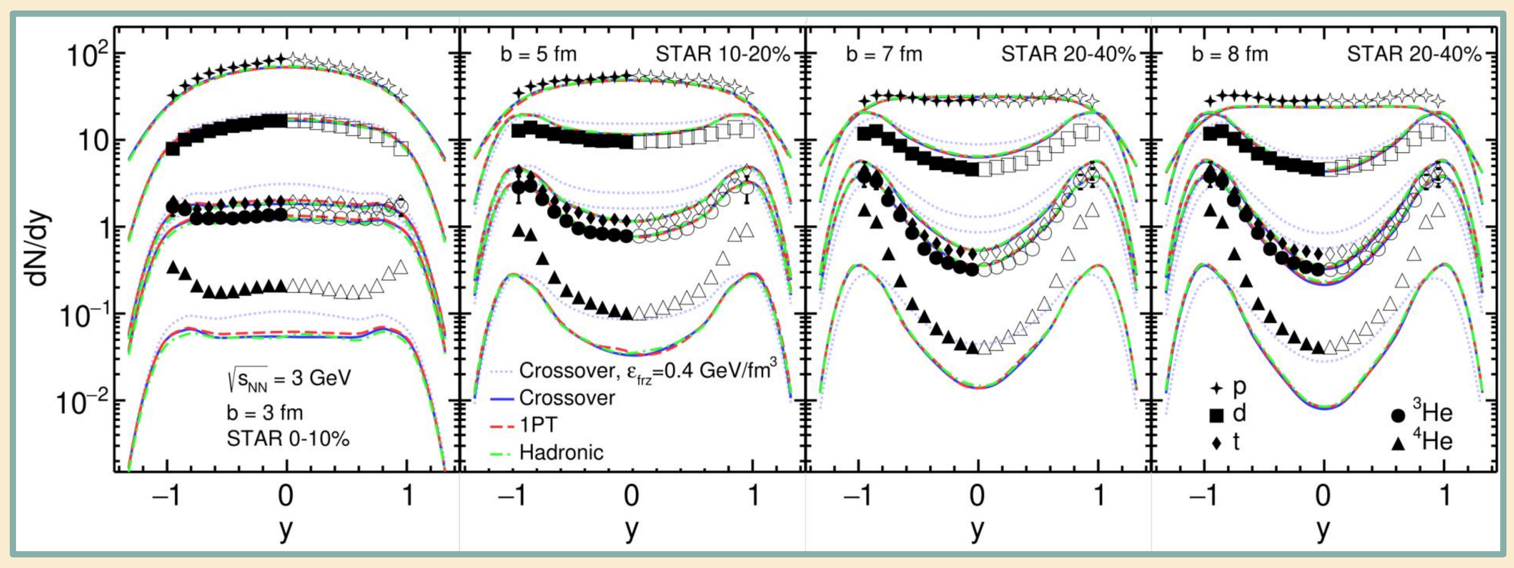


Fig.2: THESEUS results [5] on rapidity distributions of protons and light nuclei (deuterons, tritons, ^{3}He, ^{4}He) at $\sqrt{s_{NN}} = 3$ GeV in comparison with STAR data [6] calculated for three different EoS and with late freeze-out ($\varepsilon_{frz} = 0.2$ GeV/fm^3). The result with standard freeze-out ($\varepsilon_{frz} = 0.4$ GeV/fm^3) for crossover EoS is shown.

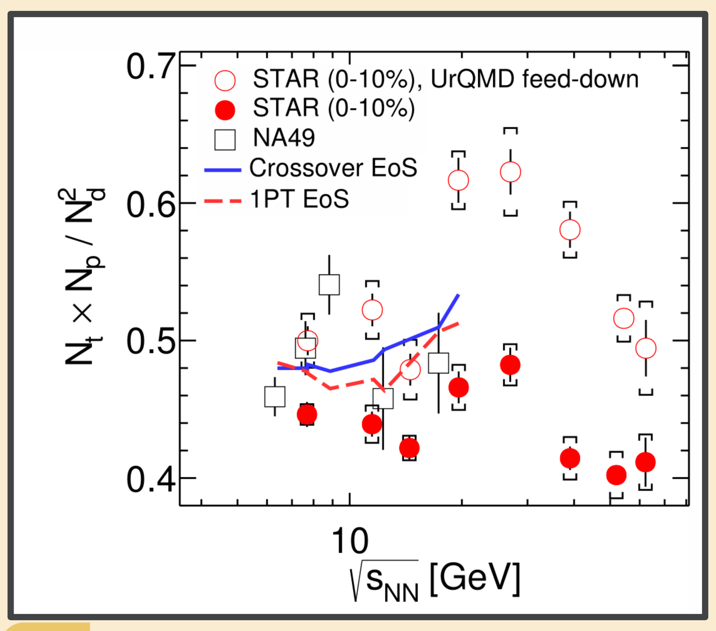


Fig.3: Energy dependence of the midrapidity light-nuclei-yield ratio in central Au+Au and Pb+Pb collisions [3]. NA49 data [4] and STAR data(preliminary [7] and final [8]) are shown.

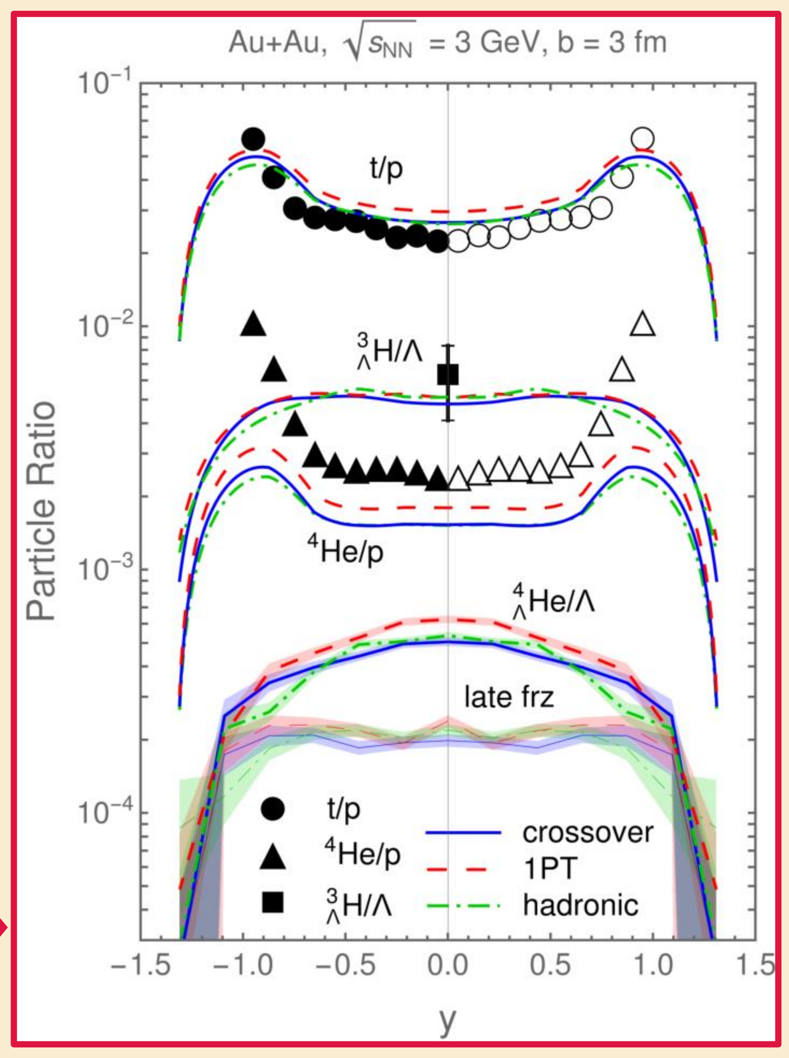
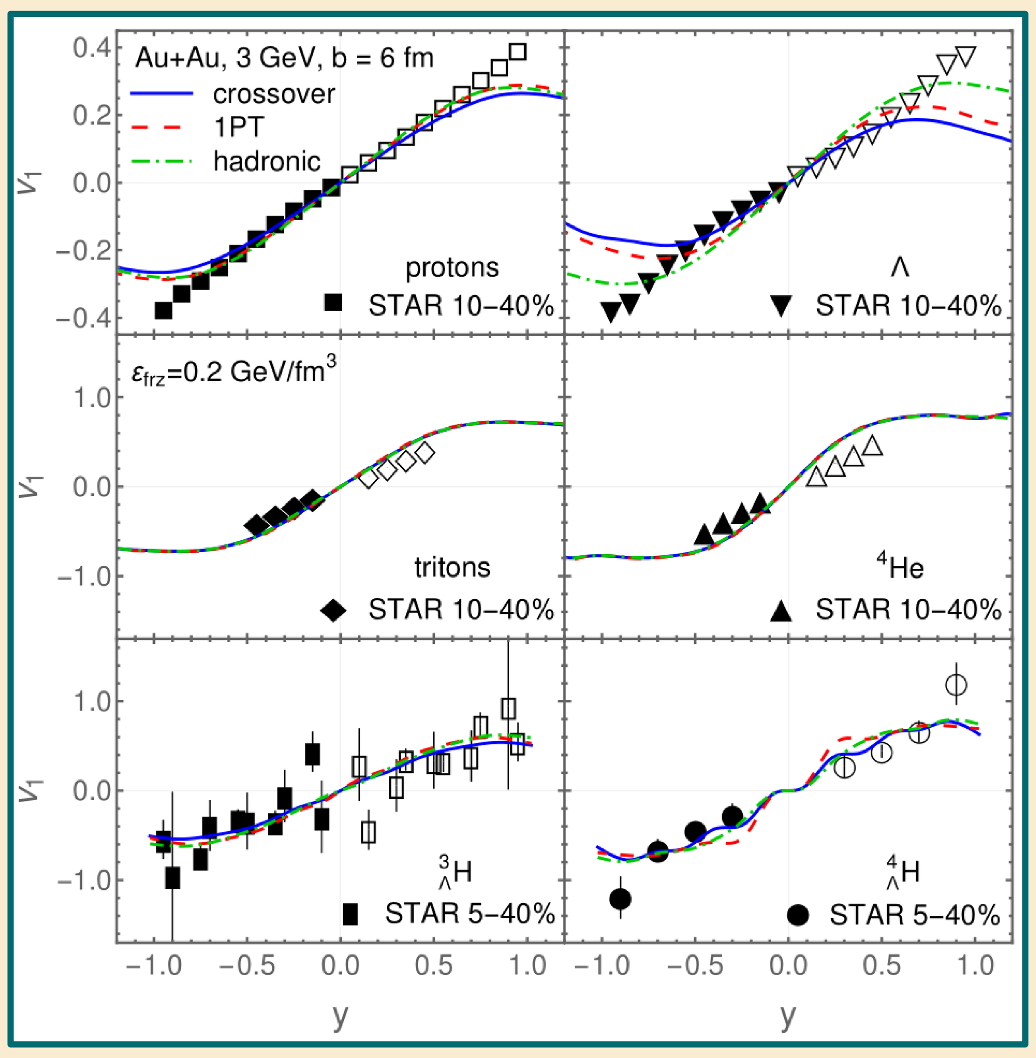


Fig.4: Particle ratios [9] in dependence of rapidity for t/p, ^{3}He/p, $^3_\Lambda$H/Λ, $^4_\Lambda$He/Λ in comparison with STAR data (Yuanjing Ji, talk at QM 2023). Different EoS are used. For p and Λ the standard freeze-out ($\varepsilon_{frz} = 0.4$ GeV/fm^3) with UrQMD afterburner is used. For t and $^3_\Lambda$He the late freeze-out $\varepsilon_{frz} = 0.2$ GeV/fm^3 is used. For ^{4}He and $^4_\Lambda$He the standard one is used.



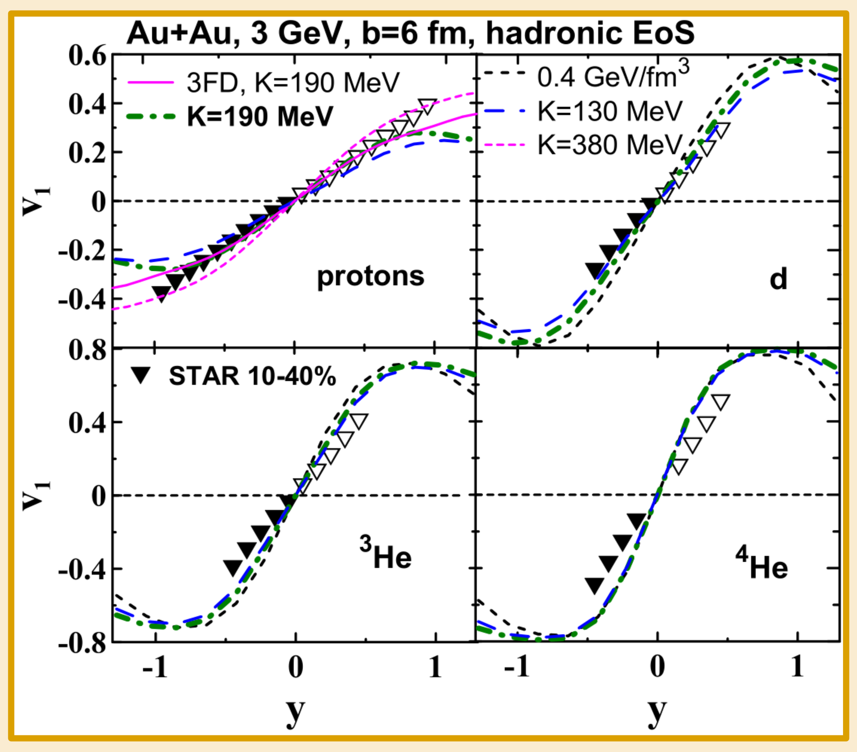


Fig.5: Directed flow of protons and light nuclei [5] as function of rapidity in semicentral (b = 6 fm) Au+Au collisions. Hadronic EoS with different stiffness K is used. Incompressibility: $K = 9n_0^2 \frac{d^2}{dn^2}\left(\frac{\varepsilon(n,T=0)}{n}\right)_{n=n_0}$, where $\varepsilon(n,T=0)$ is the energy density of the nuclear matter at $T = 0, n_0$ is the normal nuclear density.

Fig.6: Directed flow of protons, light nuclei and hypernuclei as function of rapidity in semicentral (b = 6 fm) Au+Au collisions.

3 DISCUSSION

- Afterburner of almost all light (hyper)nuclei is modelled by the late freeze-out ($\varepsilon_{frz} = 0.2$ GeV/fm^3), while ^{4}He, by standard one ($\varepsilon_{frz} = 0.4$ GeV/fm^3).
- Reasonable reproduction of data on bulk observables of the light nuclei in the energy range of $\sqrt{s_{NN}} = 3 - 19.6$ GeV.
- Ratio $N(t) \times N(p)/N^2(d)$ is considered. Accurate subtraction of weak-decays feed-down from proton yield is important.
- Good description of difference in the form of proton and light-nuclei distributions at $\sqrt{s_{NN}} = 3$ GeV and its dependence on the centrality. At $\sqrt{s_{NN}} = 3$ GeV the choice of EoS does not affect on the rapidity distributions: no phase transition takes place.
- The directed flow: good agreement of p and Λ especially in midrapidity region, no dependence on EoS for (hyper)nuclei, for hypernuclei results are in agreement with experiment within statistical uncertainties. Standard stiffness with $K = 190$ MeV is the most suitable.

4 CONCLUSION

- THESEUS gives generally good agreement of bulk observables and directed flow with experimental data. THESEUS simulations give reasonable results even for hypernuclei.
- For treatment of almost all studied (hyper)nuclei we need late freeze-out, so afterburner plays significant role in their production. An exception is ^{4}He which requires standard freeze-out.
- Dominance of hadronic phase in evolution of the system at the collision energy of $\sqrt{s_{NN}} = 3$ GeV.
- THESEUS can be used for predictions for future experiments.

REFERENCES:

[1] Yu.B. Ivanov, V.N. Russkikh, V.D. Toneev, Phys. Rev. C 73, 044904 (2006)
[2] M. Kozhevnikova et al., Phys. Rev. C 103, no.4, 044905 (2021)
[3] M. Kozhevnikova and Y. B. Ivanov, Phys. Rev. C 107, no.2, 024903 (2023)
[4] T. Anticic et al. [NA49 Collaboration], Phys. Rev. C 94, no. 4, 044906 (2016)
[5] M. Kozhevnikova and Y. B. Ivanov, Phys. Rev. C 109, no.1, 014913 (2024)
[6] M. I. Abdulhamid [STAR], [arXiv:2311.11020 [nucl-ex]].
[7] D. Zhang et al. [STAR], Nucl. Phys. A 1005, 121825 (2021) ; JPS Conf. Proc. 32, 010069 (2020)
[8] M. I. Abdulhamid et al. [STAR], Phys. Rev. Lett. 130, 202301 (2023)
[9] M. Kozhevnikova and Y. B. Ivanov, Phys. Rev. C 109, no.3, 034901 (2024)

Contact: KOZHEVNIKOVA MARINA,
JINR, LHEP, Baldin str. 4 Dubna, Russia
kozhevnikova@jinr.ru
DATE :20/01/2025