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Production of nuclei and hypernuclei in relativistic ion collisions

Alexander Botvina[1,2], *Marcus* Bleicher[1,2,3], *Nihal* Buyukcizmeci[4], and *Tom* Reichert[1,2]

[1]Institut für Theoretische Physik, J.W. Goethe University, D-60438 Frankfurt am Main, Germany
[2]Helmholtz Research Academy Hesse for FAIR (HFHF), GSI Helmholtz Center, Campus Frankfurt, 60438 Frankfurt am Main, Germany
[3]GSI Helmholtz Center for Heavy Ion Research, Planckstr. 1, D-64291 Darmstadt, Germany
[4]Department of Physics, Selçuk University, 42079 Kampüs, Konya, Türkiye

Abstract. We develop a new theoretical approach for the description of the nucleosynthesis in collisions of relativistic ions. This includes the dynamical stage, which is described by the transport UrQMD model, and the statistical stage which suggests that the nuclei and hypernuclei are formed at subnuclear density in the coexistence region of the nuclear liquid-gas type phase transition. The analysis of experimental data and new predictions support our approach.

1 Basic physic and description of the model

The production of nuclei in heavy-ion collisions is a very complicated collective process which can be effectively considered in a hybrid way with conceptually different models. It can be subdivided into a dynamical stage leading to the formation of an equilibrated nuclear system (i.e., the statistical nuclear source), and the statistical disassembly of this source leading to the formation of individual fragments. If a considerable amount of energy is deposited in the nucleus (more than 2–3 MeV per nucleon) the exited nuclear system can expand up to some freeze-out volume, and there the nuclei can be separated from uniform nuclear matter. This multifragmentation concept was confirmed with experimental and theoretical studies, and the parameters of the freeze-out volume were evaluated (see, e.g., a review [1]): It takes place at subnuclear densities from 0.1 to $0.3\rho_0$ ($\rho_0 \approx 0.15$ fm^{-3} being the ground state nuclear density). The temperatures of such systems are in the range from 5 to 8 MeV. These nuclear matter parameters correspond to the coexistence region in the nuclear liquid-gas type phase transition. Such matter at subnuclear density is the most suitable place for the formation of nuclei involving collective reactions of many baryons, even in the case of rapidly expanding of nuclear matter, where only the local equilibrium conception may be applied [2, 3].

To describe the dynamical reaction part we use the transport model UrQMD [4], which is adapted for these reactions, and is quite successful in the description of a large body of experimental data on particle production (see Refs. [4–7] and references inside). We produce initial baryons with UrQMD. In the following these baryons are collected in the primary excited clusters by using the clusterization of baryon (CB) procedure [2, 3] . The parameters of these clusters should correspond to the nuclear liquid-gas phase transition region, that can be obtained by using the velocity clusterization parameter v_c which should be around the Fermi

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velocity in nuclei. We describe the de-excitation of such clusters with the statistical multifragmentation model (SMM) [1]. This many-stage procedure leads us to the production of final nuclei. As an additional simplistic alternative to the description of the first dynamical stage we have used the phase space generation (PSG) of initial baryons according to the statistical one-particle equilibrium by taking into account the energy and momentum conservation [2, 3].

2 Comparison with experiment and predictions

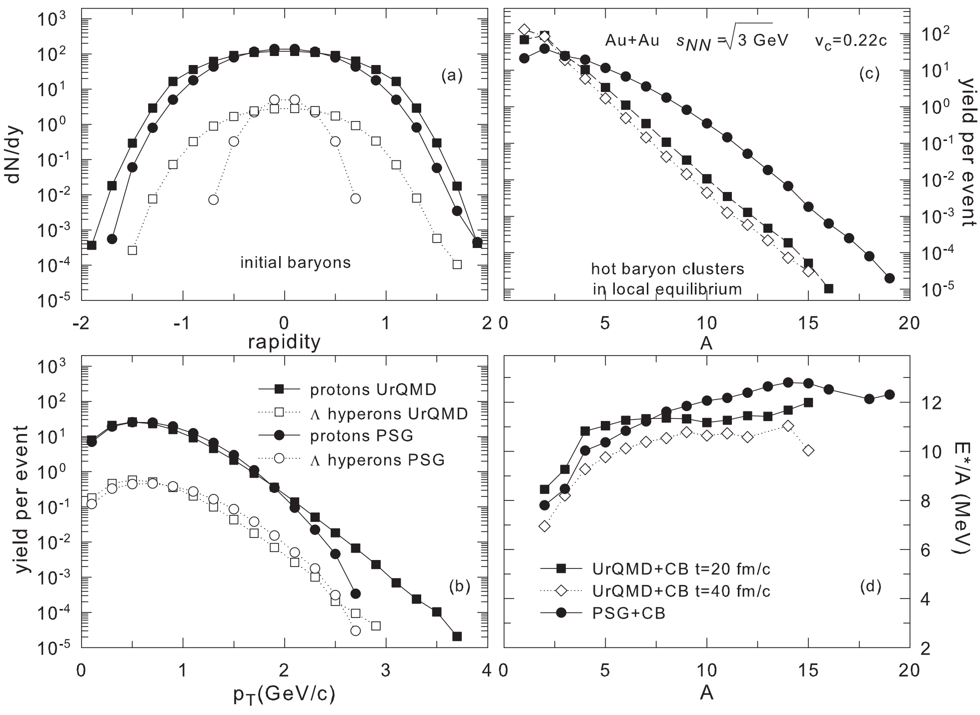

Figure 1. Left panels: Distributions of initial protons and Λ hyperons (per event) after UrQMD (impact parameters $b \leq 3$ fm) and PSG calculations for central gold-on-gold collisions at center-of-mass energy of $\sqrt{s_{NN}}$=3 GeV (see Refs. [6, 7]). Panel (a) - rapidity distributions. Panel (b) - transverse momenta distributions in the rapidity range $|y| < 0.5$. Right panels: Distributions of primary local nuclear clusters (per event) formed after UrQMD and PSG, by including the CB clusterization procedure which uses the selection of the initial baryons with the velocity and coordinate proximity. Panel (c) - mass distributions of the cluster with the CB velocity parameter v_c=0.22c. Panel (d) - average excitation energy of the clusters versus their mass number. The cut-off times for the UrQMD calculations are shown in the panels.

We analyze the production of nuclei in central Au+Au collisions at $\sqrt{s_{NN}}$=3 GeV and compare it with recent STAR data [8]. By describing the first reaction stage with UrQMD calculations we have considered the cut-off times of 20 and 40 fm/c, since between these times we expect that the produced baryons pass the subnuclear density corresponding to the coexistence region of the phase transition. The cut-off concerns mainly the coordinates of the

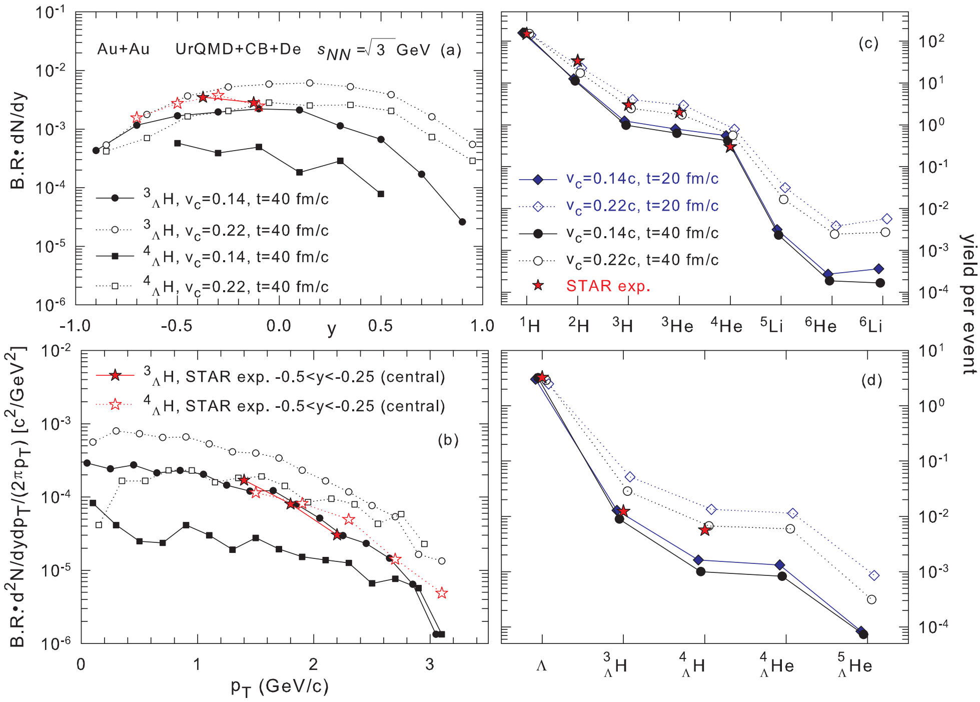

Figure 2. Comparison of the calculated production of hypernuclei and normal nuclei with STAR experimental data (see Refs. [6, 7]). The central collisions are as in Fig. 1. The calculations include the UrQMD transport, formation of excited local thermalized clusters (CB) and de-excitation of these clusters (De) with SMM. Left top panel (a) - the rapidity, and panel (b) - transverse momentum distributions of $^3_\Lambda$H and $^4_\Lambda$H hypernuclei. The model parameters and the rapidity intervals are shown in the panels. The branching decay ratios (B.R.) are taken into account in the calculations. Right panels - the predicted yields (per event) for important nuclei and hypernuclei. Panel (c) - total yields of normal nuclei. Panel (d) - yields of hypernuclei. Notations for nuclei, and the used time and v_c parameters are shown in the panels.

produced particles, but not their relative momenta, since the formation of baryons is nearly completed.

The characteristics of the produced baryons and the primary excited clusters are shown in Fig. 1. The both UrQMD and PSG cases give similar results respective to the initial distributions of particles around midrapidity, and to the sizes and excitation energies of clusters formed from these particles. The clusters are relatively small and have a considerable excitation energy, which, however, is considerably lower than the total center-of-mass energy introduced in the system. This excitation is consistent with the energy of the statistical sources extracted previously from analyses of multifragmentation data [1]. Namely the statistical evolution (decay) of these local normal- and hyper-clusters is responsible for the final yield of nuclei.

In Fig. 2 we demonstrate the final characteristics of nuclei produced after the nucleation in such clusters. As UrQMD+CB+De we denote the all three stages of the calculations, which include 1) the dynamical modelling for the baryon production, 2) the formation of several intermediate local excited baryonic clusters in chemical equilibrium at subnuclear density, and 3) the description of the nucleation process inside these clusters as their statistical decay.

We see that the suggested approach can correctly explain the main trends of the hypernuclear production, and provide consistent quantitative predictions too. The calculations are shown for different parameters which are related to the properties of nuclear (hyper-)matter inside clusters. Therefore, these properties can be determined after the comprehensive analysis of experiments. It is especially interesting that one can obtain multi-strange hypernuclei (see Ref. [7]) which is difficult to observe in traditional hypernuclear experiments. We emphasize that it is important to measure new hypernuclei and particle correlations which can be used for identification of exotic and unstable nuclei. Also a natural way to clarify the reaction mechanism is the experimental observation of the correlation of nuclei and hypernuclei after decays of primary hot clusters [5]. Relativistic heavy-ion collisions open excellent opportunities for abundant production of new nuclear species.

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