PROPERTIES AND PRODUCTION OF HYPERNUCLEI IN RELATIVISTIC ION REACTIONS*

A.S. Botvina, M. Bleicher

Institut für Theoretische Physik, J.W. Goethe University
60438 Frankfurt am Main, Germany
and
Helmholtz Research Academy Hesse for FAIR (HFHF), GSI Helmholtz Center
Campus Frankfurt, 60438 Frankfurt am Main, Germany

N. Buyukcizmeci

Department of Physics, Selçuk University
42079 Kampüs, Konya, Türkiye

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The mechanisms leading to the production of light- and intermediate-mass nuclei and hypernuclei in reactions initiated by relativistic nuclei are under study with dynamical and statistical models. We prove a novel mechanism responsible for combining nucleons and hyperons into complex nuclei in central collisions: The intermediate excited clusters of baryons can stochastically be formed at a low sub-nuclear density after the dynamical expansion of the nuclear matter. One can describe the nucleation process within the statistical approach as the disintegration of such clusters. This approach is able to describe the experimental data measured in central collisions that was not possible with other methods. The important consequence of this novel mechanism is the correlations of the produced nuclear species.

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1. Introduction

In the theory consideration, the relativistic nuclear collisions resulting into formation of small nuclei may be subdivided into several stages:

1. a dynamical stage leading to formation of an equilibrated nuclear system,

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2. the statistical fragmentation of the system into individual primary fragments, which can be accompanied by the de-excitation of hot primary fragments if they are in the excited states [1].

Many transport models are used for the description of the dynamical stage of the nuclear reaction at high energies. They take into account the hadron–hadron interactions including the secondary interactions and the decay of hadron resonances [2]. As usually accepted, the complex nuclei can be produced via interaction of the dynamically produced baryons. However, up to now, there is no clear understanding how this nuclei formation proceeds. In this contribution, we discuss a novel mechanism for these reactions.

2. Formation of nuclei and hypernuclei in high-energy reactions

It is long known that in the peripheral collisions of relativistic nuclei, one can produce projectile/target excited residual nuclei, which can be treated in the statistical way, and which decay afterwards producing many nuclei [1, 3, 4]. Usually, such residues are mainly formed from the spectator nucleons, and, in addition, they can also capture several dynamically produced nucleons and hyperons. As established in previous theoretical studies and proved by the comparison with experimental data, these highly-excited (hyper-)residues can expand to some freeze-out volume. Their subsequent fast disintegration can be described with the statistical models. This mechanism leads to the production of new nuclei and hypernuclei.

We suggest a novel promising theoretical approach to form large nuclei and hypernuclei in central relativistic nucleus collisions. At the end of the dynamical stage (at a time around $\sim$10–30 fm/c after the beginning of the nucleus–nucleus collision), many new-born baryons and nucleons escape from the colliding nuclei remnants. Some of these baryons may be located in the vicinity of each other with local subnuclear densities around $\sim 0.1\rho_0$ ($\rho_0 \approx 0.15$ fm^{-3} being the ground-state nuclear density). This nuclear matter density is very similar to the densities expected in the freeze-out volume which is assumed in the statistical approach as the proper place of the nuclei formation. Namely, in this condition, the interaction between nucleons can still lead to fragment formation from these nucleons. The system has to pass the above-mentioned density during its expansion, which allows to use the statistical models at some local space-time region.

To investigate this process, we can simulate an expanded nuclear matter state with the stochastically distributed baryons. Our first empirical method is the phase-space generation (PSG): Here, we perform an isotropic generation of all baryons of the excited nuclear system according to the microcanonical momentum phase-space distribution with total momentum and energy conservation. It corresponds to the equilibration of the one-particle degrees of freedom. However, it is not an equilibrium with respect to the nucleation process. As an alternative, we have also used the momentum generation similar to the explosive hydrodynamical generation (HYG) process, when all nucleons fly out from the center of the system. As we have demonstrated, the final results concerning the nucleation are similar despite very different distribution of initial nucleons [5, 6]. Further, we have also used the sophisticated transport models to simulate the baryon matter after the dynamical stage [2–4].

The idea is to divide the highly excited low-density nucleon matter into small parts (clusters) with nucleons which are in equilibrium respective to the nucleation process [5]. These local clusters are moderately excited, and by the expansion, they pass a low-density state which is analogous to the freeze-out states for the liquid–gas-type phase coexistence adopted in statistical models. In our calculations, we have used a coalescence of baryons (CB) model [7] and, therefore, consider them as excited coalescence-like clusters. To describe the de-excitations (*i.e.*, the fragment formation) inside these clusters, we use the statistical multifragmentation model (SMM) [1]. The SMM is very good in description of experimental data and it includes both the nuclear liquid–gas phase transition processes at high excitations and the compound nucleus decay processes at low-excitation energy.

Within our hybrid approach (consisting of the initial dynamics, stochastic clustering, and statistical decay models), we are able to describe the nuclei yields, their kinetic energies, and the isotope composition simultaneously, including their evolution with the beam energy. As an example, in Fig. 1, we demonstrate the description of the FOPI experimental data [8]. All other corresponding comparisons and theoretical details can be found in Refs. [5, 6]. This success gives us the confidence to apply the theory for the hypernuclei production in relativistic ion collisions.

The velocity proximity parameter v_{c} is used for the baryon selection into the excited clusters. However, this parameter is only a technical one, since it is naturally related to the excitation energy of the cluster. Namely, this excitation has the main physical meaning for cluster selection. Figure 2 shows the excitation energies most suitable for reproducing experimental data. For the correct description of experimental data, the excitation energies of such clusters should be in the range of 6–10 MeV per nucleon, that is close to the corresponding nuclear binding energies. We believe it is one of the important results indicating the condition for the application of the statistical methods in the nucleation process.

In order to calculate the hypernuclei yields in high-energy nucleus collisions, we need yields of both nucleons and hyperons after the dynamical reaction stage, therefore, we have involved UrQMD and DCM models [2, 4]. Similar to the normal nuclei case, the intermediate coalescent-like excited

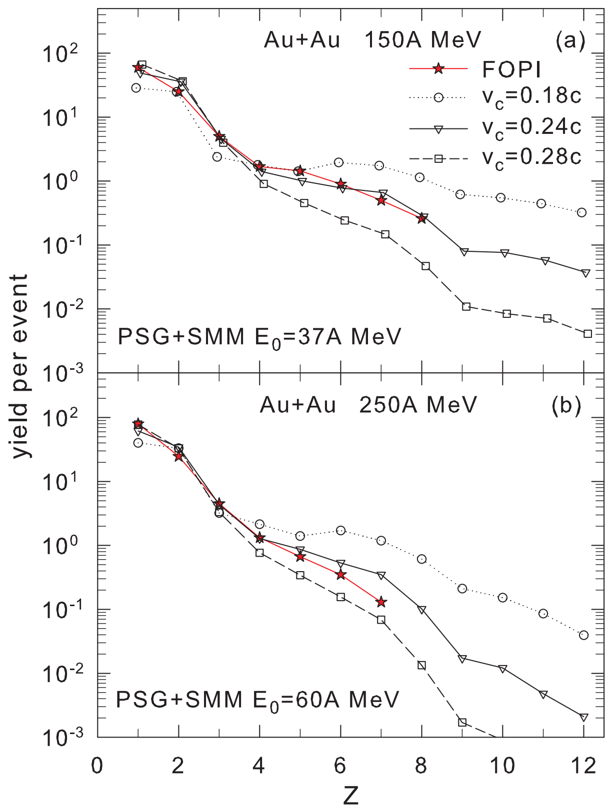

Fig. 1. Comparison of the calculated nuclei yields with the FOPI experimental data on the nuclei production in central Au+Au collisions at 150 A MeV (panel (a)) and 250 A MeV (panel (b)). The parameters of the initial source are given in the figure. The nucleon distributions are after PSG and for the parameters, see Ref. [6].

hyper-clusters can be produced at low density and their decay leads to the hypernuclei production. As an example, in Fig. 3, we show the yields of some light hypernuclei. The important result is that these hypernuclei are formed in correlations with other particles, which can be experimentally measured for the mechanism verification (see also Fig. 3). With our statistical approach, we can also investigate the properties of the produced hypernuclei by comparing their isotope yields. As demonstrated in Ref. [9], the binding energies of the exotic hypernuclei can be evaluated.

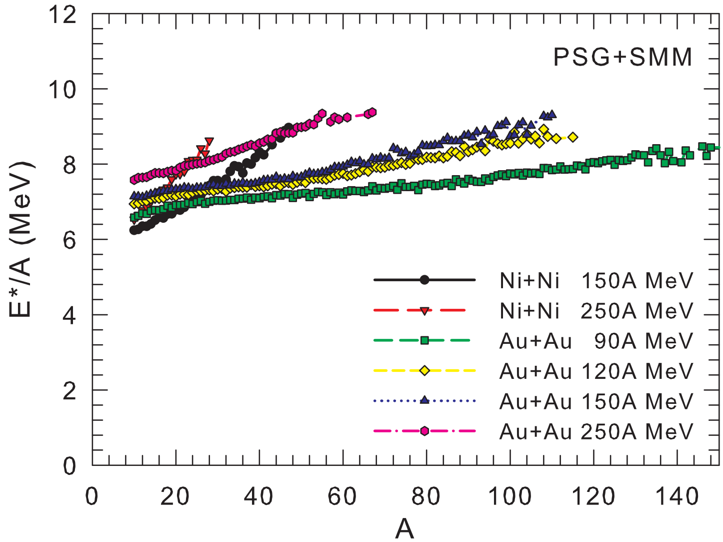

Fig. 2. Average excitation energy per nucleon (E^*/A) of the clusters of nuclear matter in local chemical equilibrium *versus* their mass number A corresponding to the $v_{\rm c}$ parameters which lead to the best description of the FOPI experimental data. The lines correspond to different reactions of central collisions, they are noted in the figure, see Ref. [6].

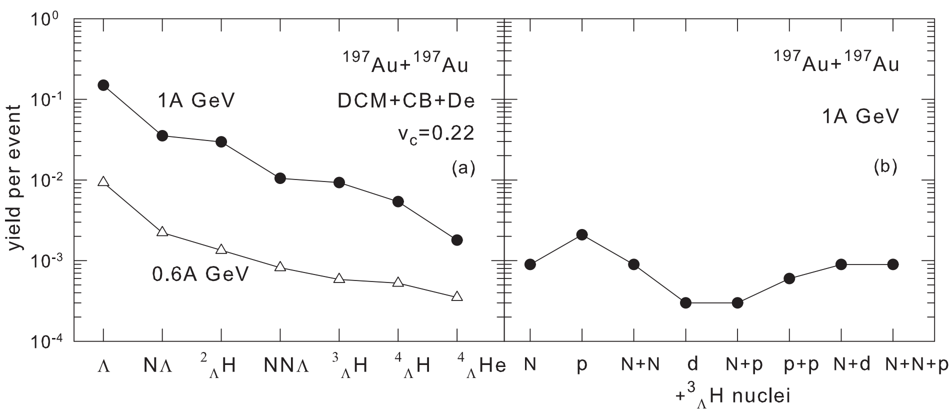

Fig. 3. Yields of hypernuclei produced in central collisions of two gold nuclei calculated with the combination of transport (DCM), coalescence (CB), and SMM de-excitation (DE) models. Panel (a) presents the full yields per event. The yields of correlated particles (neutrons, proton, deutrons) in channels with the $^{3}_{\Lambda}$H production are shown in panel (b). Beam energies are indicated in panels (a) and (b). See Ref. [5] for other details.

3. Conclusion

We have suggested a new theoretical approach to explain the light- and intermediate-fragment yields after the expansion of highly-excited finite nuclear-matter systems. For the first time we have succeeded to describe consistently the experimental data obtained in the central nucleus–nucleus collisions [5, 6]. It is important that the correlations of the produced particles can be a consequence of this kind of fragment formation. We believe that this approach which combines:

1. the adequate dynamical models for the first reaction stage,
2. the formation of intermediate local equilibrized sources at subnuclear density, and
3. the statistical description of the following nucleation process as the decay of these sources,

should be used in future at high-energy reactions for the nuclei prediction. It will give us the possibility to analyze new nuclear species formed from various baryons, *e.g.*, hypernuclei [5], which can be abundantly produced in central collisions.

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