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Production of nuclei and hypernuclei in relativistic ion reactions

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Abstract. We study the production of small nuclei, nuclei of intermediate mass, and hypernuclei in relativistic nuclear reactions by using dynamical and statistical models. We propose a novel mechanism responsible for the formation of complex nuclei from nucleons and hyperons produced in collisions: In this reaction the excited clusters consisting 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 such clusters with the statistical models. We suggest the hybrid approach allowing for the consistent description of the experimental data measured in central collisions, which was not possible with other theoretical methods. The important consequence of this novel mechanism is the correlations of the produced nuclear species. The energy limits for describing the fragmentation and nucleation processes in excited finite nuclear systems with statistical models are also obtained.

1. Introduction

It is commonly accepted in the theory that the relativistic nuclear collisions resulting into formation of many nuclei can be subdivided into several stages: (1) a dynamical stage leading to formation of an equilibrated nuclear system, (2) the statistical fragmentation of the system into individual fragments, which can be excited and undergo the de-excitation into the final 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]. Depending on the nuclear matter condition after the fast dynamical interaction the complex nuclei can be produced both via interaction of the new produced baryons and via decay of the excited nuclei. 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

As was established during the last decades in the peripheral collisions of relativistic nuclei one can produce projectile and target excited residual nuclei, which decay afterwards with the production of many nuclear species. This decay can be treated in the statistical way [1, 3, 4]. Usually such residues are mainly formed from the spectator nucleons remaining in interacting nuclei, and, in addition, several dynamically produced nucleons and hyperons can also be captured. It was found in previous theoretical studies and proved by the comparison with experimental data that there are at least two mechanisms for their de-excitation: At relatively low excitations the process proceeds via the compound nucleus formation. However, highly-excited residues can expand and decay in some freeze-out volume [1]. This is a 'multifragmentation' disintegration which can be described with the statistical models. It leads to the production of nuclei and hypernuclei in the diluted and excited nuclear matter.

Another physical picture is taking place in between the target and projectile, and in central collisions, where the new complex nuclei are formed from the nucleons knocked out after the interaction. In this contribution we propose a novel theoretical approach to form light nuclear fragments, intermediate mass nuclei, and hypernuclei in central collisions of relativistic nuclei. At the end of the dynamical stage (on time around ∼10-30 fm/c after the beginning of the nucleus-nucleus collision) many new-born baryons and nucleons are escaped from the nuclear remnants. Some of these baryons will be located in the vicinity of each other at the local subnuclear densities around $\sim 0.1\rho_0$ ($\rho_0 \approx 0.15$ fm^{-3} being the ground state nuclear density). Such a nuclear matter density is very similar to the densities expected in the freeze-out volume which is considered in the statistical approach as the proper place for the formation of new nuclei. Namely at this condition the interaction between nucleon can lead to fragment formation from the participating nucleons. The above-mentioned density is naturally passed during the nuclear matter expansion after the collision, therefore, the situation allows to use the statistical models at this local space-time region.

We can specially simulate an expanded nuclear matter state with the stochastically distributed baryons to investigate this process in details [5, 6]. As our first empirical method we suggest the phase space generation (PSG): We perform an isotropic generation of all baryons in the excited nuclear system according to the microcanonical momentum phase space distribution with total momentum and energy conservation. Such procedure corresponds to the equilibration according to the one-particle degrees of freedom. However, it is still not an equilibrium with respect to the nucleation process. As an alternative we have also used the momentum generation including the explosive hydrodynamical generation (HYG) process, when all nucleons fly away from the center of the system. We have demonstrated that the final results concerning the nucleation are similar despite very different distribution of initial nucleons [5, 6]. And as the final promising development we have suggested to use the sophisticated transport models to simulate the baryon matter after the dynamical stage [2, 3, 4].

Our 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]. Under construction these local clusters are moderately excited, therefore, 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. To select nucleons into clusters we have used a coalescence of baryons (CB) model [7] and consider the excited coalescence-like clusters. To describe their de-excitation which leads to the fragment formation inside these clusters we use the statistical multifragmentation model (SMM) [1]. The SMM was very good in description of experimental data and it combines both the nuclear liquid-gas phase transition processes at high excitation and the compound nucleus decay processes at low excitation energy.

We have formulated the hybrid approach consisting of the initial dynamics, stochastic clustering, and statistical decay models. It is instructive that we have succeeded to describe the nuclei yields, their kinetic energies, and the isotope composition simultaneously, including the evolution of the yields with the beam energy. As a representative example, in Fig. 1 we demonstrate the description of the FOPI experimental data [8]. One can see that the yields can be reproduced by selecting the adequate parameters v_c, which determine the cluster properties. Other corresponding comparisons and theoretical details one can find in Refs. [5, 6]. Such a successful analysis was not possible to perform with the previous models existed in the market:

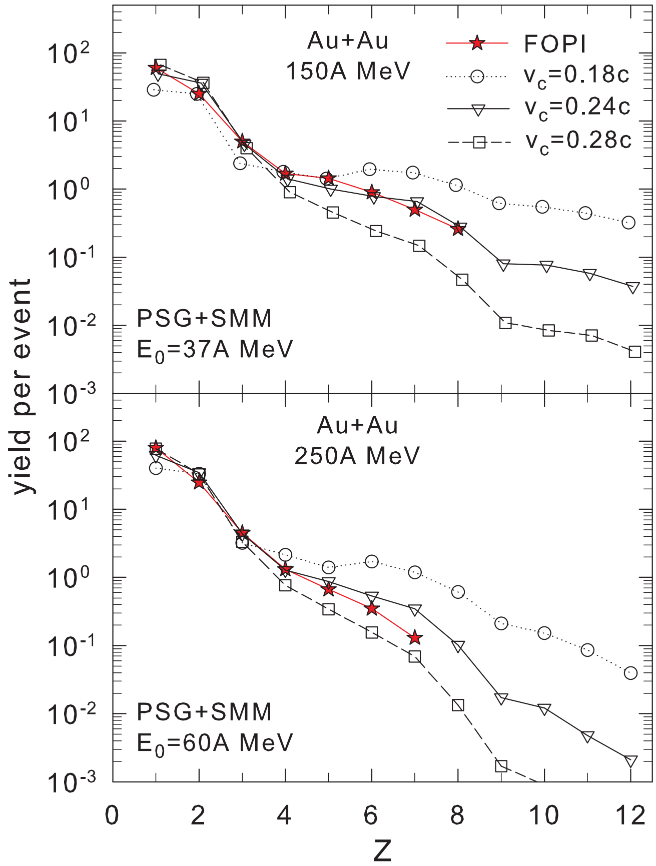

Figure 1. Comparison of the calculated nuclei yields with the FOPI experimental data on the nuclei production in central Au+Au collisions at 150 A MeV (top panel) and 250 A MeV (bottom panel). The primary nucleons are distributed after PSG. The initial source parameters are given in the figure, and for other model parameters see Ref. [6].

Usually, the dynamical models have the problems with the realistic construction of complex nuclei from energetic baryons, whereas the statistical models are not able to describe consistently the kinetic energy of nuclei. In our approach we have overcome these problems, and this success gives us a confidence to apply the proposed theory for the hypernuclei production in relativistic ion collisions.

As a by-product of our analysis we have obtained the important result concerning the condition for the application of the statistical conception in the nucleation process: The velocity proximity parameter v_c is used in our procedure for the baryon selection into the excited clusters [5, 6, 7]. However, this parameter is only an auxiliary (intermediate) one, since it is naturally related to the excitation energy of the cluster under local equilibrium. This excitation has the main physical meaning and should be finally used for the cluster definition independently on the technical method of the cluster selection. Fig. 2 shows the excitation energies most suitable for the consistent reproduction of all experimental data. In order to describe correctly the data the excitation energies of such clusters should be in the range of 6–10 MeV per nucleon. These values are close to their nuclear binding energies, and it can be a boundary condition characterizing the many-body phenomena in finite excited nuclei. The same maximum values for the excited nuclear sources were extracted from the analysis of the projectile multifragmentation [1, 9]. We

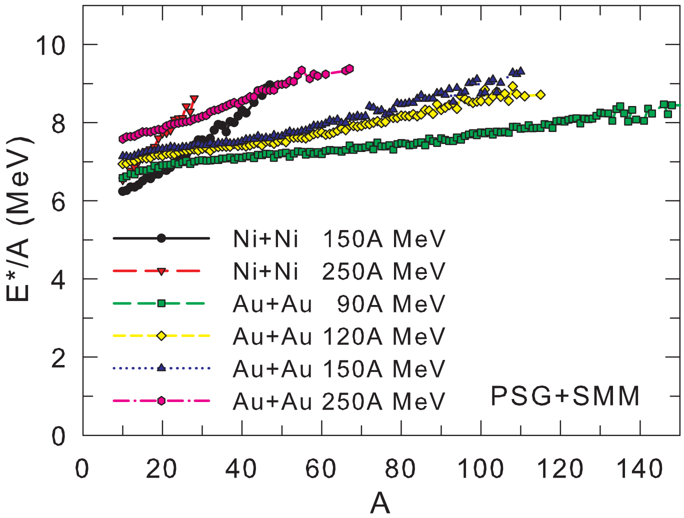

Figure 2. Average excitation energy per nucleon (E^*/A) of the clusters of nuclear matter in local chemical equilibrium versus their mass number A, which corresponds to the v_c parameters leading to the best description of the FOPI experimental data. The lines indicate different reactions of central collisions, as they are noted in the figure, see Ref. [6].

believe it is a natural energy limit for applying the statistical description of the nucleation and fragmentation reactions in nuclear systems.

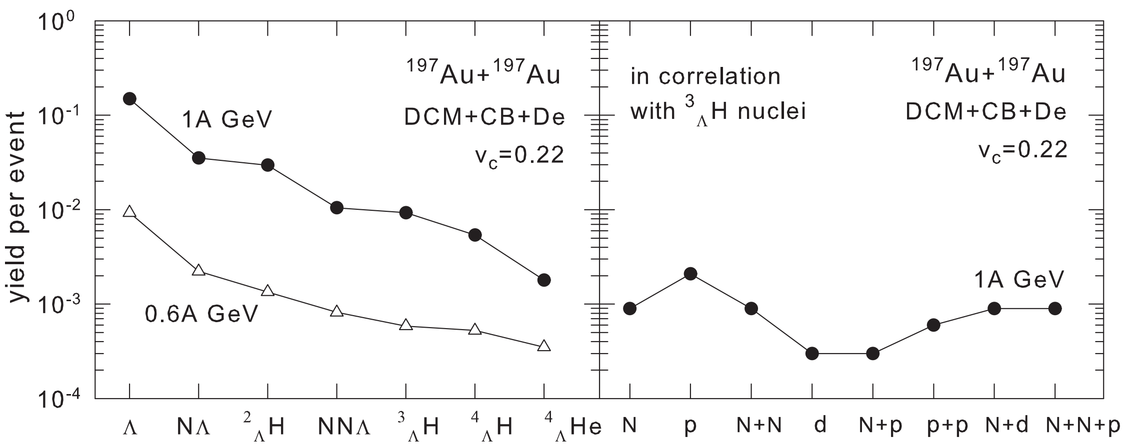

Figure 3. Yields of hypernuclei produced in central collisions of two gold nuclei are calculated with our approach consisting of the combination of transport (DCM), coalescence (CB), and SMM de-excitation (DE) models. The left panel presents the full yields per event. Yields of the correlated particles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

In order to calculate the hypernuclei yields in high energy nuclear collisions we need first to evaluate the yields of both nucleons and hyperons after the dynamical reaction stage. Therefore, we have involved UrQMD and DCM models [2, 4]. Similar to the reactions with normal nuclei the intermediate coalescent-like excited hyper-clusters can be separated at low density and their decay leads to the hypernuclei production. For example, in Fig. 3 we show the yields of some light hypernuclear species. The important conclusion is that these hypernuclei are formed in correlations with other particles, which are produced in the decay of same clusters where the hypernuclei are formed (see also Fig. 3). All these particles can be experimentally measured. It should be a solid way to verify this reaction mechanism. Many additional possibilities for the hypernuclear research can be open within our theoretical approach by analyzing exotic hypernuclei produced in relativistic ion collisions. For example, one can evaluate the binding energies of the hypernuclei by comparing their isotope yields, as was demonstrated in Ref. [10]. A great variety of produced hypernuclei is an important advantage of these collisions in comparison with traditional hypernuclear methods concentrated on reactions leading only to few species.

3. Conclusion

We have developed a new theoretical approach to explain the light and intermediate fragment yields after the nuclear collisions and the following expansion of highly excited finite nuclear-matter systems. For the first time have succeeded to describe consistently the experimental data obtained in central nucleus-nucleus collisions [5, 6]. Another important conclusion is that the correlations of the produced particles can be a consequence of this kind of the fragment formation. It is also instructive that as a result of the analysis we have confirmed a prescription for using the statistical conception for the decay of finite excited nuclear systems with some limitation: As usually, at low excitation energies (up to 2–3 MeV per nucleon) one can use the compound nucleus assumption. At higher energies, up to 6–10 MeV per nucleon, we should assume that the nuclei fastly expand and should use the freeze-out volume conception to describe the fragmentation. At very high excitation energy ($\geq$10 MeV per nucleon) we can not assume the statistical equilibrium for the whole system (respective to the nucleation process), and we should subdivide the system into small clusters and apply the local equilibrium conception for the nuclei production.

We believe that our approach combining 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 nucleation process as the decay of these sources should be used in future at high energy reactions for the prediction of final yields of nuclei. It will give us a possibility to analyze unknown nuclear species formed from various baryons, e.g., hypernuclei [5], which can be abundantly produced in central and peripheral collisions.

Acknowledgments

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