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Nucleation of Rapidly Expanding Nuclear Matter in Intermediate Energy Nuclear Reactions

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Abstract. The formation of light nuclei in the rapidly expanding nuclear matter after intermediate energy nucleus-nucleus collisions is investigated. It is demonstrated that this phenomenon can be explained within the statistical approach by applying the local equilibrium concept. We subdivide the expanding nuclear system into several parts (primary clusters) consisting of nucleons which are close in phase space. The nucleation process takes place inside these clusters, and it can be described as their statistical decay in the coexistence region of the nuclear liquid-gas phase transition. This approach is a natural generalization of the well-known compound nucleus concept, and the freeze-out volume concept developed for multifragmentation reactions. The local equilibrium concept allows to explain consistently many experimental data, that was not possible with the statistical models under assumption of global chemical equilibrium. We extend this approach by including the dynamical and statistical stages for the description of the nucleosynthesis in central collisions of relativistic ions.

1 Introduction

On the surway of the recent results on the nuclei formation in heavy ion reactions [1–5], in this study we have focused on the products of the central Ni+Ni collisions around intermediate energies. At high energies some fragment formation properties may disappear and/or change, but for the realistic modelling it is always necessary to test model calculations for nuclear collisions starting from lower to higher energies. We have used the Phase Space Generation (PSG) method [6–8] within the Statistical Multifragmentation Model (SMM) [9] to describe formation of light nuclei. Model calculations are applied in three steps as follows: generation of the initial nucleon/baryon distribution(s), identification of clusters, and statistical decay of excited clusters. The initial nucleon distributions are determined using the PSG method as in [6–8, 10]. Conservation of total energy and momentum and produce nucleon momenta strongly correlated with nucleon coordinates. In the second stage, hot clusters are "identified" based on nucleon relative velocities v_c via clusterization of of baryons (CB) in local equilibrium. In the third stage, SMM is employed to obtain the final nuclei, hypernuclei and double hypernuclei (as in Refs. [7, 8, 10, 11]). We have also discussed single excited source in chemical equilibrium. We call as global equilibrium to this assumption, after collision there will be a compound nucleus and depending on the excitation energy of this big cluster only limited number of light nuclei can be formed in the system. Especially, in this study mainly we have compared two cases by assuming for single excited source decay in global chemical equilibrium and multiple chemical sources in local equilibrium in the expanding matter.

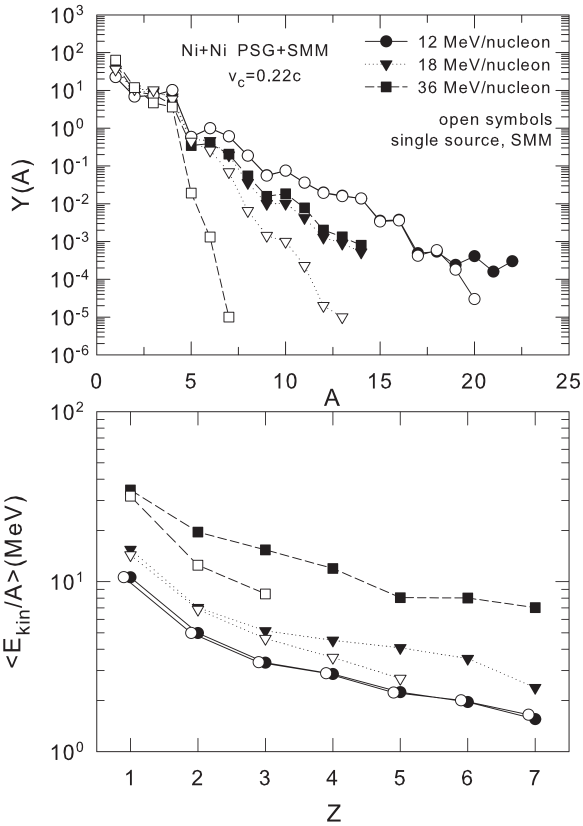

Figure 1. The yield per event of nuclei versus masses number A (top panel) and the average kinetic energies per nucleon of charged nuclei Z (bottom panel) in the local equilibrium (full symbols, the calculations with PSG+SMM), and in the global equilibrium (open symbols, the calculations with SMM) for Ni+Ni central collision at energies of 12, 18, and 36 MeV per nucleon.

2 Mass Distributions and Kinetic Energy Spectra of Light Charged Nuclei

In Figure 1, top panel shows the yield per event of final nuclei versus mass number A and the bottom panel shows kinetic energies of final nuclei versus charge number Z in the local equilibrium (full symbols, the calculations include PSG+SMM), and in the global equilibrium (open symbols, the calculations done with SMM only) for Ni+Ni central collision at energies of 12, 18, and 36 MeV per nucleon. In the top panel, while the mass distributions decreases with increasing mass number with increasing energy, in global equilibrium assumption case these decreasing trend dominate with increasing energy. While the average kinetic energy per nucleon for light charged nuclei does not change at around 12 MeV per nucleon for global and local equilibrium case. There is a clear difference around higher energies (such as 18 and 36 MeV per nucleon) for global and local equilibrium case in the bottom panel of Figure 1.

As illustrated in Figure 1, as the source energy increases, there is a rather smooth transition in the characteristics of final nuclei between the cases of global and local equilibrium. While the local equilibrium results in increased yields of large nuclei (top panel), and the kinetic energies become higher than in the global equilibrium (bottom panel). In general, the global equilibrium at high excitation energy of the source encourages the disintegration of the system into very small fragments, while the local equilibrium effectively appears a part of this disintegration energy into the kinetic energy of the produced nuclei.

3 Conclusion

Since the nucleosynthesis of nucleons can occur in the region of transition from the heavy-ion beams of Fermi energy to the beams with several hundred MeV per nucleon, in this study, we focused on mechanism of fragment formation in central Ni+Ni ion collisions at intermediate energies. New nuclei are composed in the expanding nuclear matter due to the existing of the attractive interaction between nucleons, which is calculated in our case within the statistical approach. We show that this approach worked perfectly at intermediate energy by describing FOPI data [7], it is extracted that the excitation energies of the local excited sources should coincide around 6-10 MeV per nucleon, it is the signature of universal mechanism for the nuclear fragment production and independent on v_c. We have demonstrated mass distributions and kinetic energy spectra of light nuclei at energies starting from 12 MeV per nucleon to 36 MeV/nucleon for the nucleosynthesis of hadrons to form nuclei processes by using PSG method and taking into account their deexcitation, the parameters of the hot nuclear matter in the clusters should be with the parameters of finite nuclear systems extracted from multifragmentation studies. On the basis of these kind of results by using local and global equilibrium assumption to form new nuclei, we will implement similar methods to test the generalized SMM for the hypernuclei and double hypernuclei formation in Ref. [10] at higher energies. We believe that it would be worthwhile to present results for nuclei, hypernuclei and double hyper nuclei at higher energies by comparing full hybrid model calculations PSG+SMM and SMM, and also extend for other physical quantities, such as radial and directed flow, which are still under investigation.

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