Production of hypernuclei in multifragmentation of nuclear spectator matter

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In peripheral collisions of relativistic heavy ions highly excited spectators containing Λ hyperons can be produced. Such strange spectator matter may undergo a break-up into many fragments (multifragmentation) as it is well established for ordinary nuclear systems. We generalize the statistical multifragmentation model, previously successfully used for the description of experimental data, for the case of hypernuclear systems. We predict relative yields of hypernuclei and the main characteristics of such a breakup. We point at a connection of this phenomenon with a liquid-gas phase transition in hypermatter.

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I. INTRODUCTION

One promising way to study hypernuclei is to use the copious production of hyperons in relativistic heavy ion collisions. As seen in experiments in the GeV range [1], Λ hyperons originating from the hot participant region have a broad rapidity distribution and a considerable fraction can be found in the spectator kinematical region. In peripheral collisions these Λ hyperons may be captured by excited spectators. Subsequently these spectators may decay producing cold and possibly exotic hypernuclei. It has been demonstrated experimentally that the cross section of this reaction may be on the order of a few microbarns [2]. A similar value can be obtained with ultrarelativistic quantum molecular dynamics (UrQMD) calculations by assuming a coalescence of the produced Λ hyperons with spectators [3]. Indeed there are extensive plans to investigate hypernuclei produced in such heavy ion reactions using stable [2] as well as exotic beams [3].

An important feature of these reactions is a correlation between the excitation energy transferred to the spectator matter and the number of high energy particles produced as a result of collisions between nucleons in the participant region (see, e.g., [4]), which are also related to the strangeness production. As a consequence the excited spectators break-up into many fragments (multifragmentation) [5–7], and the captured Λ will be finally attached to these fragments. According to the present understanding, multifragmentation is a relatively fast process, with a characteristic time around 100 fm/c, where, nevertheless, a high degree of equilibration (chemical equilibrium) is reached [8]. This is a result of the strong interaction between the nucleons, and we believe that a small admixture of other particles like hyperons interacting with similar cross sections [9] will not change the general statistical behavior. Multifragmentation can also be associated with the liquid-gas phase transition in nuclear systems, and thermodynamical features of this transition were experimentally investigated [10]. As was demonstrated by numerous comparisons of theory and experiment, statistical models allow a successful description of experimental data [5,7,11,12]. In this paper we demonstrate that multifragmentation of hypermatter can be described in a similar way, and some properties of hypernuclei can be explored by examining relative yields of hyperfragments. The calculations also show that the usage of exotic heavy ion beams will indeed allow to produce hypernuclei with extreme N/Z ratios and thus hypernuclei which are not experimentally accessible with any other technique.

II. STATISTICAL FRAGMENTATION OF FINITE HYPERMATTER SYSTEMS

For the theoretical description of this process we modify the grand-canonical version of the statistical multifragmentation model (SMM) [5,13]. Previously, this version, with explicit addition of mass, charge, energy, and momentum conservations, was successfully used for the description of multifragmentation in relativistic heavy-ion reactions [7,11,12]. Microcanonical extensions of statistical models, such as [14], are essential only for a few details of the phase transition, but not for the general description of the produced fragments. The model assumes that a hot nuclear spectator with total mass (baryon) number A_0, charge Z_0, number of Λ hyperons H_0, and temperature T expands to a low density freeze-out volume, where the system is in chemical equilibrium. The statistical ensemble includes all break-up channels composed of nucleons and excited fragments. The primary fragments are formed in the freeze-out volume V. We use the excluded volume approximation $V = V_0 + V_f$, where $V_0 = A_0/\rho_0$ ($\rho_0 \approx 0.15$ fm^{-3} is the normal nuclear density), and parametrize the free volume $V_f = \kappa V_0$, with $\kappa \approx 2$ [7,11,12].

Nuclear clusters in the freeze-out volume are described as follows: light fragments with mass number $A < 4$ are treated as elementary particles with corresponding spin and translational degrees of freedom ("nuclear gas"). Their binding energies were taken from experimental data [5,15,16]. Fragments with $A = 4$ are also treated as gas particles with table masses, however, some excitation energy is allowed $E_x = AT^2/\varepsilon_0$ ($\varepsilon_0 \approx 16$ MeV is the inverse volume level density parameter [5]), that reflects the presence of excited states in ^{4}He, $^4_\Lambda$H, and $^4_\Lambda$He nuclei. Fragments with $A > 4$ are treated as heated liquid drops. In this way one can study the nuclear liquid-gas coexistence of hypermatter in the freeze-out volume. The internal free energies of these fragments are parametrized as the sum of the bulk (F_A^B), the surface (F_A^S), the

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symmetry ($F^{\rm sym}_{\rm AZH}$), the Coulomb (F^C_{AZ}), and the hyperenergy ($F^{\rm hyp}_{\rm AH}$):

$$F_{\rm AZH}(T,V) = F^B_A + F^S_A + F^{\rm sym}_{\rm AZH} + F^C_{AZ} + F^{\rm hyp}_{\rm AH}. \quad (1)$$

Here, H denotes the number of Λ's. The first three terms are written in the standard liquid-drop form [5]: $F^B_A(T) = (-w_0 - \frac{T^2}{\varepsilon_0})A$, $F^S_A(T) = \beta_0(\frac{T_c^2-T^2}{T_c^2+T^2})^{5/4}A^{2/3}$, and $F^{\rm sym}_{\rm AZH} = \gamma \cdot (A-H-2Z)^2/(A-H)$. The model parameters $w_0 = 16$ MeV, $\beta_0 = 18$ MeV, $T_c = 18$ MeV and $\gamma = 25$ MeV were extracted from nuclear phenomenology and provide a good description of multifragmentation data [5,7,11,12]. The Coulomb interaction of the fragments is described within the Wigner-Seitz approximation, and F^C_{AZ} is taken as in Ref. [5].

The new term is the free hyperenergy $F^{\rm hyp}_{\rm AH}$. We assume that it does not change with temperature, i.e., it is determined solely by the binding energy of the hyperfragments. Presently, only a few tens of masses of single hypernuclei (mostly light ones) are experimentally established [15,16], and there is only very limited information on double hypernuclei available. However, there are some theoretical estimations of their masses based on a description of the available data. One of them is the Samanta formula [17] which suggests a hyperterm

$$E^{\rm hyp}_{sam} = H \cdot (-10.68 + 48.7/(A^{2/3})). \quad (2)$$

The contribution proportional to $A^{-2/3}$ is motivated by calculations of the Λ binding energy in a potential well [18]. In what later follows we use $F^{\rm hyp}_{\rm AH} = E^{\rm hyp}_{sam}$ as one of the versions for our calculations. We have also explored another hyperterm (in the following we call it the liquid drop hyperterm):

$$F^{\rm hyp}_{\rm AH} = (H/A) \cdot (-10.68A + 21.27A^{2/3}). \quad (3)$$

In this formula the binding energy is proportional to the fraction of hyperons in the system (H/A). The second part represents the volume contribution reduced by the surface term and thus resembles a liquid-drop parametrization based on the saturation of the nuclear interaction. The linear dependence at small H/A is in agreement with theoretical predictions [19] for hypermatter. We have found that for single hypernuclei with $A > 8$ the average deviation of the liquid-drop masses from the experimental masses tabulated in [15] is 1.8 MeV, while using the Samanta formula this deviation is worse and amounts to 2.2 MeV. If not mentioned otherwise we use the liquid-drop hyperterm in the following.

At this point we should note that the properties of the primary fragments may change in the medium compared to the vacuum due to the proximity of other fragments. Presently, there are evidences that the symmetry energy [20–22] and surface energy [23] of hot fragments in multifragmentation may be modified. However, these corrections are not large and influence multifragmentation in finite nuclear systems very little. They are more important for astrophysical applications [24]. Moreover, since the binding energies of hypernuclei are mostly not known even in vacuum, this problem is naturally included in searching for a reliable mass formula for hypernuclei within this approach.

The break-up channels should be selected according to their statistical weight. In the grand canonics this leads to the following average yields of individual fragments:

$$Y_{\rm AZH} = g_{\rm AZH} V_f \frac{A^{3/2}}{\lambda_T^3} \exp\left[-\frac{1}{T}(F_{\rm AZH} - \mu_{\rm AZH})\right],$$
$$\mu_{\rm AZH} = A\mu + Z\nu + H\xi. \quad (4)$$

Here $g_{\rm AZH}$ is the ground-state degeneracy factor of species (A,Z,H), $\lambda_T = (2\pi\hbar^2/m_N T)^{1/2}$ is the nucleon thermal wavelength, $m_N \approx 939$ MeV is the average nucleon mass. In our case $H \ll A$, therefore, the mass difference between nucleons and Λ can be disregarded in this expression. The chemical potentials μ, ν, and ξ are responsible for the mass (baryon) number, charge, and strangeness conservation in the system. They can be found from the balance equations:

$$\sum_{\rm AZH} AY_{\rm AZH} = A_0, \quad \sum_{\rm AZH} ZY_{\rm AZH} = Z_0, \quad \sum_{\rm AZH} HY_{\rm AZH} = H_0.$$

Within this extended SMM approach we have performed calculations for excited spectator sources which can be produced during peripheral relativistic heavy ion collisions. Below, we show results for heavy systems with $A_0 = 200$ and $Z_0 = 80$, and intermediate systems with $A_0 = 100$ and $A_0 = 50$, varying the charge-to-mass ratio (Z/A) from 0.4 to 0.5, and H_0 from 0 to 2. The first source has the mass and Z/A ratio typical for a heavy projectile. We expect the most extensive absorption of Λ hyperons by spectators in the case of heavy projectiles and targets. It will be possible to increase the strangeness production by selecting smaller impact parameters, leading to a higher excitation and a smaller mass of the projectile spectators. However, previous analyses [20] suggest that their Z/A ratio will be nearly conserved.

III. PRODUCTION OF HYPERNUCLEI AND THEIR PROPERTIES

In Fig. 1 we present the average multiplicity of fragments produced after the breakup of the excited spectators, the caloric curve for these breakups, and the chemical potential ξ, versus the temperature of the spectator matter. At small temperatures ($T < 3$ MeV), the compound nucleus channel ($M = 1$) dominates. In the following it should decay by means of evaporation or fission processes [5]. One can consider it as a nuclear liquid phase. At temperatures $T = 4$–6 MeV the system produces mainly several intermediate mass fragments (IMF, with $4 < A \lesssim A_0/3$), however, a heavy residue and light particles are also possible. In nuclear multifragmentation this region is interpreted as a liquid-gas phase coexistence [5,10]. Here the caloric curve signals an increasing heat capacity, associated with a rapid rise of the excitation energy. And at high excitations ($T > 8$–9 MeV) the system disintegrates mainly into light particles (a gas phase). One can see that the small admixture of Λ's does not change this general behavior. However, a drop of ξ at $T > 4$ MeV signals a decreasing average strangeness content of the fragments.

In the top panel of Fig. 2 we explicitly demonstrate this decrease of the average number of Λ's contained in the fragments with rising temperature. In three bottom panels we show how the mass distributions of fragments evolve

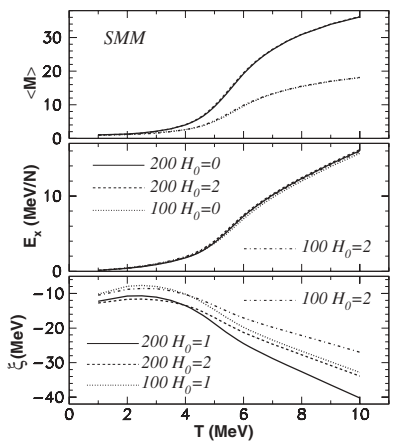

FIG. 1. SMM calculations of multifragmentation of spectator sources with $A_0 = 200$, $Z_0 = 80$ and $A_0 = 100$, $Z_0 = 40$, with number of Λ hyperons $H_0 = 0, 1, 2$. Top panel – average multiplicity of produced primary fragments (notations are as in the middle panel), middle panel – excitation energy of the sources (caloric curve), bottom panel – chemical potential ξ responsible for strangeness, as function of temperature T.

with the temperature. Around the onset of multifragmentation ($T \approx 4$ MeV) there is a "U-shaped" distribution with a big residue and few small fragments. The residue contains nearly all strangeness of the system, while the small fragments are mainly without hyperons. Also the share of free Λ's is not essential, hyperons prefer to be bound in fragments in all cases. When the system breaks into many fragments, the strangeness is distributed among all produced IMF. Within the phase coexistence region ($T \approx 5$ MeV) we have a rather flat distributions for the produced big residues, and nearly equal probabilities for producing the residues with different number

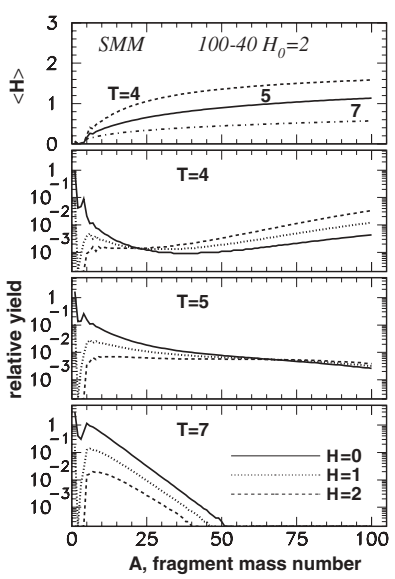

FIG. 2. Multifragmentation of sources with $A_0 = 100$, $Z_0 = 40$, $H_0 = 2$. Top panel – average number of hyperons in fragments at temperatures $T = 4$, 5, and 7 MeV. Three bottom panels – relative yields of fragments (per event), separately for fragments containing $H = 0$, 1, or 2 Λ, at the same temperatures.

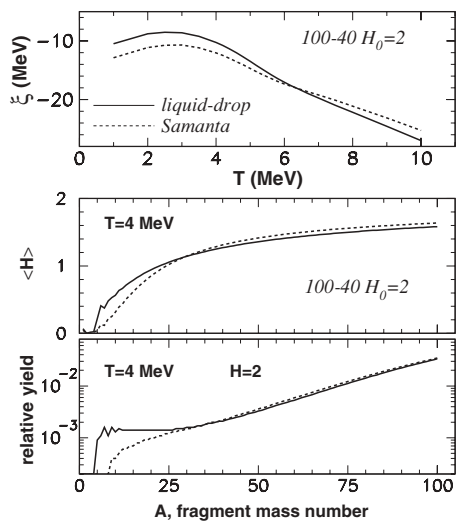

FIG. 3. Comparison of SMM calculations with the liquid-drop and Samanta descriptions of hyper terms in the mass formula, for the same sources as in Fig. 2. Top panel – the strangeness chemical potential ξ versus temperature T. Middle panel – average number of Λ hyperons in fragments, and bottom panel – yields of fragments with two Λ, at $T = 4$ MeV.

of hyperons. Large fluctuations of number of fragments and their size are expected in this case.

We have found that there is a sensitivity of the fragment yields in multifragmentation to the mass formulas used for description of binding energy of hypernuclei. In Fig. 3 we compare SMM calculations performed with the liquid-drop hyperterm (3) in free energy of individual fragments, and with the Samanta term (2). There is a clear difference in the chemical potential ξ, and, as a result, the yields of hyperfragments are also different. As one can see from the bottom panels the liquid-drop formula predicts more strangeness in IMF's than the Samanta formula. The difference in the yields is particularly large for small double hyperfragments. In future, this observable may allow to test experimentally different mass formulas for hypernuclei in multifragmentation.

It is an important feature that the isotope composition of the produced hypernuclei can be varied considerably in these reactions. In Fig. 4 we show charge distributions of fragments with $A = 30$ after the breakup of spectator sources with different isospin. The corresponding Z_0/A_0 ratios can be easily obtained by selecting different projectiles. After multifragmentation, the hot primary fragments have approximately the same average isospin content as the sources, whereas the widths of the charge distributions depend mainly on the fragment symmetry energy [14]. Thus the present work shows that it is indeed possible to produce very neutron rich hyperfragments. We expect that the final isospin distributions will be similar to the ones reported in previous multifragmentation studies with exotic beams [21,22].

After the breakup, the Coulomb acceleration and the secondary deexcitation of primary hot fragments should be taken into account [5]. As it is well known from calculations and experiments, the deexcitation of nuclei with $A \leqslant 200$ will proceed mainly by emission of nucleons. As a consequence

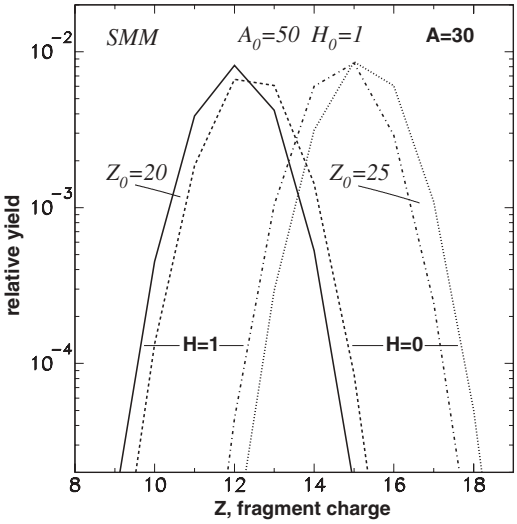

FIG. 4. Charge distributions of primary fragments with $A = 30$ produced after break-up of sources with $A_0 = 50$, $H_0 = 1$, $Z_0 = 20$ (solid and dashed lines), and $Z_0 = 25$ (dotted and dot-dashed lines), at temperature $T = 5$ MeV. $H = 0$ stands for fragments without Λ, $H = 1$ are fragments with one Λ.

the resulting distributions of cold nuclei are not very different from the primary ones, they are just shifted to lower masses. In this case the reported regularities will not change, and the differences in relative yields will survive, though some of them may become smaller [5,21,22]. The last stage will be the mesonic or nonmesonic decay of hypernuclei which can used for the identification of the hypernuclei [3].

IV. CONCLUSIONS

We conclude that multifragmentation reactions offer a new possibility for investigating hypernuclei under conditions essentially different from those accessible in conventional nuclear structure studies. One of the advantages is that in this reaction one can abundantly produce hypernuclei with unusual Z/A ratios. It is encouraging that one can distinguish between different mass formulas of hypernuclei, since their properties are manifested in their relative yields. More generally, we suggest that this reaction can be considered as an experimental tool to study clusterization of nuclear matter with strangeness, and the phase diagram of hypernuclear matter at densities $\rho \approx 0.1$–$0.3\rho_0$ and temperatures around $T \approx 3$–8 MeV reached in the freeze-out volume. Apparently, such a phase transition may take place in some astrophysical cases, for example, in neutron star crusts.

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