In-medium properties of nuclear fragments at the liquid-gas phase coexistence

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Abstract

Reactions of nuclear multifragmentation of excited finite nuclei can be interpreted as manifestation of the nuclear liquid-gas phase transition. During this process the matter at subnuclear density clusterizes into hot primary fragments, which are located in the vicinity of other nuclear species. In recent experiments there were found evidences that the symmetry and surface energies of primary fragments change considerably as compared to isolated cold or low-excited nuclei. The new modified properties of primary fragments should be taken into account during their secondary de-excitation.

Multifragmentation has been observed in nearly all types of high energy nuclear interactions induced by hadrons, photons, and heavy ions (see a review [1]). This is an universal phenomenon occurring when a large amount of energy is deposited in a nucleus, and a hot blob of nuclear matter is formed. The matter will expand to the sub-saturation densities, where it becomes unstable and breaks up into many fragments. Multifragmentation is a fast process, with a characteristic time around 100 fm/c, where, however, a high degree of equilibration can be reached. For this reason, multifragmentation opens a unique experimental possibility for investigating the phase diagram of nuclear matter at temperatures $T \approx 3 - 8$ MeV and densities around $\rho \approx 0.1 - 0.3 \rho_0$ ($\rho_0 \approx 0.15$ fm$^{-3}$ is the normal nuclear density). These conditions are typical for the liquid-gas coexistence region, and they are reached in the freeze-out volume at multifragmentation. It is interesting that similar
In Fig. 1 we demonstrate a schematic phase diagram of nuclear matter which has a liquid-gas phase transition. The shaded area at subnuclear densities indicates the region of densities and temperatures which can be studied in nuclear multifragmentation processes. We have also shown isentropic trajectories with $S/B$ values of 1, 2, and 4 typical for stellar processes leading to supernova explosions. One can see, for example, that a nearly adiabatic collapse of the massive stars with typical entropies of 1-2 per baryon passes exactly through the multifragmentation area.

The Statistical Multifragmentation Model (SMM) [1] is very successful in description of experimental data. It is based on the assumption of statistical equilibrium between produced fragments in a low-density freeze-out volume. We believe that at this point the chemical equilibrium is established, i.e., the baryon composition (mass and charge) of primary fragments is fixed. However, the hot primary fragments are formed in close vicinity to each other, and, therefore, they are still subject to Coulomb and, possibly, residual nuclear interactions. Hence, the fragment energies and densities are
affected by this interaction. It is commonly accepted that the liquid-drop description of individual nuclei is very successful in nuclear physics. In the SMM the fragments with $A > 4$ are treated as heated nuclear liquid drops, and their individual free energies $F_{AZ}$ are parameterized as a sum of the bulk, surface, Coulomb and symmetry energy terms:

$$F_{AZ} = F_{AZ}^B + F_{AZ}^S + E_{AZ}^C + E_{AZ}^{sym}. \quad (1)$$

In this standard expression $F_{AZ}^B = (-W_0 - T^2/\epsilon_0)A$ is the bulk energy term including contribution of internal excitations controlled by the level-density parameter $\epsilon_0$, and $W_0 = 16$ MeV is the binding energy of nuclear matter. $F_{AZ}^S = B_0 A^{2/3} ((T_c^2 - T^2)/(T_c^2 + T^2))^{5/4}$ is the surface energy term, where $B_0 = 18$ MeV is the surface coefficient, and $T_c = 18$ MeV is the critical temperature of infinite nuclear matter. The Coulomb energy is $E_{AZ}^C = cZ^2/A^{1/3}$, where $c$ is the Coulomb parameter obtained in the Wigner-Seitz approximation, $c = (3/5)(e^2/r_0)(1 - (\rho/\rho_0)^{1/3})$, where $r_0 = 1.17$ fm, and the last factor describes the screening effect due to presence of other fragments. $E_{AZ}^{sym} = \gamma (A - 2Z)^2/A$ is the symmetry energy term, where $\gamma = 25$ MeV is the symmetry energy coefficient. These parameters are taken from Bethe-Weizsäcker formula and corresponding to the isolated fragments with normal nuclear density. This assumption has been seen to be quite successful in description of experimental data concerning charge and thermodynamical characteristics of produced fragments [4–10]. However, in a multi-fragment system in the freeze-out volume, the parameters of the liquid-drop model may change as compared with those for isolated nuclei.

In recent years new experiments related to the nuclear isospin and isotope distributions in multifragmentation reactions have been performed [11–13]. The statistical analyses of the isotope data have led to a conclusion that modifications of the liquid-drop parameters of hot fragments produced in the freeze-out volume are needed to explain the experiments. It was suggested that the physical reason of this effect could be a new physical environment where fragments are formed. The residual interactions may lead to energy and density changes which can effectively be explained by a modification of the macroscopic nuclear parameters. In particular, it is consistent with predictions of many dynamical models that hot fragments formed in a dilute nuclear matter have a reduced density too. As known from equations of state, the symmetry energy of nuclei decreases at subnuclear densities [14]. The symmetry energy coefficient $\gamma$ was investigated in the INDRA/ALADIN experiment [11] by using the isoscaling phenomenon. As demonstrated in Fig. 2, the coefficient $\gamma$ is about 25 MeV for peripheral collisions, as known
Figure 2: The apparent symmetry energy coefficient $\gamma$ of hot nuclei, as extracted from multifragmentation of tin isotopes induced by $^{12}$C beams with energy 300 and 600 MeV per nucleon, versus relative impact parameter $b/b_{\text{max}}$ [11].

Figure 3: Mean neutron-to-proton ratio versus charge of fragments produced in multifragmentation-like break-up of $^{238}$U with energy 1 GeV/nucleon on Pb and Ti targets [3]. Points are experimental data obtained on Fragment Separator (FRS) at GSI. The dashed line is SMM calculation for primary hot fragments, solid and dot-dashed lines are fragments after secondary de-excitation. Dotted line 1 corresponds to stable nuclei, dotted line 2 is the EPAX phenomenological parametrization for nuclei produced by spallation. The solid and dashed lines are calculations at the standard symmetry energy parameter $\gamma = 25$ MeV, the dot-dashed line is for reduced $\gamma = 15$ MeV.
for cold isolated nuclei. It drops down to ≈ 15 MeV for more central collisions leading to multifragmentation reaction. The same evolution of γ for hot primary fragments was also extracted from the TAMU experimental data obtained in central and peripheral nucleus-nucleus collisions around Fermi energy [12, 13]. In these experiments, besides the isoscaling, the neutron-to-proton (N/Z) ratio in produced fragments, and the fragments isotope distributions were analysed. Other high quality experimental data on mean N/Z ratio of produced fragments, obtained in a FRS experiment at GSI, are demonstrated in Fig. 3. The best description of intermediate mass fragments (IMF: Z = 3−20), which are produced mainly at multifragmentation, can be obtained with the SMM at the reduced γ also [3]. It is important that all experimental analyses of the isotope characteristics come to the conclusion that there is a decreasing of the coefficient γ to around 15 MeV for hot primary fragments at multifragmentation conditions.

A recent analysis of the ALADIN data has revealed modifications in the nuclear surface properties too [15]. The N/Z dependence of the surface energy was investigated for different event classes corresponding to different excitation energies. At low excitation energies, corresponding to the onset of multifragmentation, the surface energy follows the trend predicted by the standard liquid-drop model, i.e., it decreases with N/Z, see Fig. 4. This trend is usually explained by the contribution of the surface part of the symmetry energy. In the region of developed multifragmentation, where IMF are mostly produced, the surface energy coefficient becomes nearly independent of the N/Z ratio. Taking into account this result we conclude that subdivision of the total symmetry energy into volume and surface parts becomes irrelevant at multifragmentation conditions. We point out that similar conclusions about changing surface properties of nuclei were obtained within the dynamical AMD model [16]. Therefore, the observed decrease of the symmetry energy of fragments should not be related to the increase of the total surface of fragments at multifragmentation. The new surface properties complement the medium modification of γ coefficient in the system of many fragments.

At the last stage of the multifragmentation process hot primary fragments undergo de-excitation and propagate in the mutual Coulomb field. In the beginning of the de-excitation the hot fragments are still surrounded by other species, and, therefore, their modified properties should be taken into account. As far as we know, only one evaporation code was designed, which takes into account the modified properties of fragments in their de-excitation. It was developed in refs. [17], where modifications of symmetry energy were explicitly considered. Namely, the secondary de-excitation
Figure 4: The extracted surface energy coefficient $B_0$ for ensemble sources with different $N/Z$ ratios at the onset ($Z_{\text{bound}}/Z_0=0.85$ bin), and at the region of full multifragmentation ($Z_{\text{bound}}/Z_0=0.65$ and 0.55 bins) [15]. The width of the shaded band represents limits given by our method for the lowest bin. The $B_0$ obtained from Cameron (C) and Myers-Swiatecki (MS) mass formulae for cold nuclei are shown by solid lines for illustration.

starts from the modified symmetry energy of hot nuclei and restore their normal properties by the end of the evaporation cascade. The energy and momentum conservation laws were fulfilled in the course of this evaporation process. We emphasize that this de-excitation stage should be consistent with the physical mechanism of production of primary fragments. For example, a failure to describe the experimental isoscaling data [18], by using a dynamical BNV model for primary fragment formation, may be related to the fact that the sequential evaporation of the fragments was included without paying attention to their reduced densities, and, as a result, to their small symmetry energies. As was demonstrated in [17, 12] this can influence isotope distributions, because separation energies of neutrons and protons change essentially. We believe that besides the isotope information and isoscaling, the relevant analyses should include the corresponding fragment charge distributions, IMF multiplicities, temperatures and other information [4–10, 15].

We conclude that statistical models, which are successfully applied for description of nuclear multifragmentation, can be used for extended analyses of the hot fragments embedded in surrounding of other nuclei and nucleons,
typical for the liquid-gas phase coexistence. Input parameters of the statistical models (e.g., the symmetry and surface energies of primary fragments) can be directly extracted from multifragmentation experiments. There are evidences of reduction of the fragment symmetry energy, and modification of their surface energy, which are obtained in analyses of independent experiments, and they are consistent with model predictions. It is important that for self-consistent description of the whole process the secondary de-excitation of primary fragments should take into account the modified properties, at least, in the beginning of evaporation cascade. One of the goals of future multifragmentation experiments is to determine properties of fragments, which are formed in hot nuclear systems at subnuclear densities.

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