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ON NUCLEAR LIQUID-GAS PHASE TRANSITION VIA MULTIFRAGMENTATION AND FISSION

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Introduction

For the last years the problem of a liquid-gas phase transition in the hot nuclear matter has been widely discussed [1–6]. There are two methods to create very hot nuclei. The first one is collision of nuclei with comparable masses at the energies up to several hundreds MeV per nucleon. This way of heating is followed by compression and rotation of the system. The second way is the reaction induced by relativistic light ions in which excited target spectators are created. In this case the dynamics effects connected with the compression and rotation of the system are negligible and the target spectator can be treated as pure thermally excited. Now it is well established that the main decay mode of very hot nuclei is a copious emission of intermediate mass fragments (IMF, $3 \leq Z \leq 20$). According to number of models this process is definitely influenced by the nuclear liquid-gas phase transition and the multifragmentation study is the way to eliminate that very intriguing problem.

In recent paper [7] the experimental data on Au + Au collisions at 600 MeV/nucleon have been presented as a possible signature of the liquid-gas phase transition in nuclear matter. The multifragmentation of the projectile spectator was studied with the ALADIN-spectrometer which supplied exclusive data on the process. The temperature of the fragmenting system was obtained by measuring the yield ratios for He and Li isotopes. The mean excitation energy of the decaying system was determined by a total energy balance after evaluation of the masses and energies of all the particles involved in the process. These data are shown in Figure 1 together with the points measured earlier for heavy ion collisions at lower energies. For the energies below 3 MeV/nucleon the temperature is growing with the energy according to the expectation for a Fermi-liquid. After that a plateau at the temperature of 5 MeV is observed ranging from 3 MeV/nucleon up to 10 MeV/nucleon. At higher energies the temperature is going up linearly with the energy as for the gas of classical particles. Such behaviour is considered to be evidence for a first-order phase transition with significant latent heat and the critical temperature $T_c = 5$ MeV. This value is remarkably smaller than the one predicted by various models for the nuclear liquid-gas phase transition (15–18 MeV).

One should remember that the surface tension vanishes at the critical temperature. Below the critical point the surface tension gradually reduces when the nuclear temperature approaches the critical one. So one should expect the dramatic reduction of the fission barrier at nuclear temperature (2–3) MeV if $T_c = 5$ MeV. The temperature effects in the fission barriers for that range of T were already considered in ref. [8–11] but for the "normal" critical temperature around (15–18) MeV.

In this paper we consider the T-dependence of the liquid-drop fission barrier with the critical temperature as a parameter. It is found that the calculated fission probabilities of the medium-heavy nuclei at the excitation energies around 100 MeV are significantly larger than the measured ones, if T_c is assumed to be around 5 MeV.

Temperature dependence of fission barrier

In terms of the usual liquid-drop notation [12] the fission barrier as a function of temperature can be calculated by the relation

$$\begin{aligned} B_f(T) &= E_s(T_s) - E_s^\circ(T) + E_c(T_s) - E_c^\circ(T) = \\ &= E_s^\circ(T)[(B_s - 1) + 2x(T)(B_c - 1)], \end{aligned} \quad (1)$$

where B_s is the surface (free) energy at the saddle point $E_s(T_s)$ in units of surface energy $E_s^\circ(T)$ of the spherical drop, B_c is the Coulomb energy $E_c(T_s)$ at the saddle deformation in units of Coulomb energy $E_c^\circ(T)$ of the spherical nucleus. For the surface energy and fissility parameter $x(T)$ one can write [8]:

$$\begin{aligned} &E_s^\circ(T) = E_s^\circ(0)\sigma(T)/\sigma(0) \cdot [n(0)/n(T)]^{2/3} \\ &x(T) = \frac{E_c^\circ(T)}{2E_s^\circ(T)} = x(0)\frac{n(T)}{n(0)} \cdot \frac{\sigma(0)}{\sigma(T)}, \end{aligned} \quad (2)$$

where $\sigma(T)$ and $n(T)$ are the surface tension and the mean nuclear density for a given temperature T. As a first approximation, we neglect the difference between the temperature at the saddle T_s and T. In that case the values B_s and B_c are determined by the deformation at the saddle point, which depends on the fissility parameter $x(T)$. They are tabulated by Nix [12] for the full range of the fissility parameter.

For $\sigma(T)$ the approximation from ref. [13] is used:

$$\sigma(T) = \sigma(0)\left[\frac{T_c^2 - T^2}{T_c^2 + T^2}\right]^{5/4}. \quad (3)$$

The expressions for $E_s^\circ(0)$ and $x(0)$ are taken from [11]:

$$\begin{aligned} &E_s^\circ(0) = 17.94\gamma \cdot A^{2/3}\ \text{MeV} \qquad x(0) = \frac{Z^2/A}{50.88\gamma} \\ &\gamma = 1 - 1.7826[(N-Z)/A]^2. \end{aligned} \quad (4)$$

In paper [9] the thermal properties of nuclei are investigated using the Hartree-Fock approximation with the Skyrme force. The equation of the state was obtained which gives the critical temperature $T_c = 18$ MeV. For that case the temperature dependence of the mean nuclear density is found as $n(T) = n(0)(1 - \alpha T^2)$ with $\alpha = 1.26 \cdot 10^{-3}$ MeV^{-2}. If in fact T_c has another value the parameter α is also changed. We assume $\alpha \sim T_c^{-2}$ as in the case of $\sigma(T)$ for $T \ll T_c$.

Using the results of [9] we get

$$n(T) = n(0)(1 - 0.4T^2/T_c^2). \quad (5)$$

Figure 2 presents the relative values of $\sigma(T)$, $n(T)$ and $x(T)$ as a function of T/T_c. One should expect drastic change in nuclear fissility even half way to the critical point. Figure 3 shows the calculated liquid-drop fission barries for ^{188}Os as a function of temperature. It practically vanishes for $T > 0.4T_c$. This nucleus has been chosen as it presents a good example for the comparison of the calculated and experimental data.

Estimation of fission probability

The first-chance fission probability $\Gamma_f/(\Gamma_f+\Gamma_n)$ is calculated by the relation of Moretto [14]:

$$\frac{\Gamma_f}{\Gamma_n}=\frac{\pi\hbar^2}{4m\sigma_{CN}}\frac{T_s}{T_R^2}\frac{\rho_s(E-B_f)}{\rho_R(E-B_n)}\,, \qquad (6)$$

where ρ_s is th level density at the saddle point, ρ_R and T_R are the level density and the temperature of the residual nucleus (after neutron emission), m and σ_{CN} are the neutron mass and the capture cross-section. For the level density the expression from the Fermi-gas model is used

$$\rho(E^*)=\frac{\sqrt{\pi}}{12}\frac{1}{a^{1/4}(E^*)^{5/4}}\exp(2\sqrt{aE^*})\,.$$

The level density parameter for fission a_f is usually taken slightly larger than for neutron evaporation a_n. In this paper we believe $a_f = a_n = \frac{A}{10}$ having in mind significant diminishing of the fission barrier.

Figure 4 presents the results of calculations of the fission probabilities for ^{188}Os assuming $T_c = 5$ MeV and $T_c = 10$ MeV as a function of the excitation energy. We restricted ourselves to the temperature range (2–2.5) MeV as the calculations were made under the assumption that $T_s = T$. The experimental points for fission in ^{4}He + ^{184}W collisions are taken from ref. [15].

The curve going through the points is a result of theoretical fit made in [15] with a fission barrier $B_f = 24.2$ MeV, corrected for the shell effects. These experimental data definitely exclude $T_c = 5$ MeV. Even $T_c = 10$ MeV should be also excluded though the assumption $T_s = T$ is not as good as in the case of $T_c = 5$ MeV, but it is compensated for by the fact that the actual value of a_f is larger than a_n (according to ref. [15] $a_f = 1.08\,a_n$ for ^{188}Os).

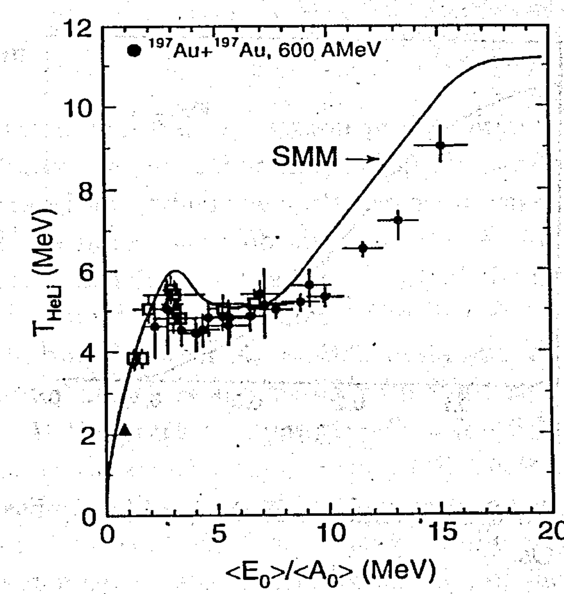

Fig. 1. Temperature as a function of the excitation energy per nucleon. The experimental data are from [7]. The line is calculated for $A_\circ = 100$ in ref. [16] with Copenhagen's statistical model of multifragmentation.

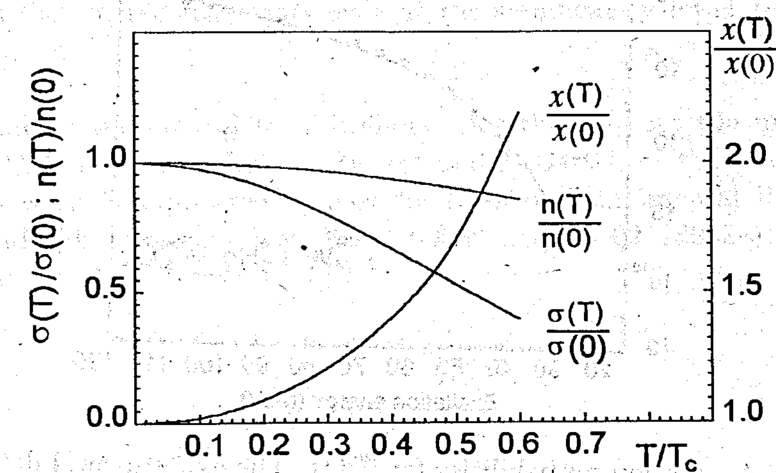

Fig. 2. Relative values of the surface tension, mean nuclear density and fissility parameters as a function of temperature in the units of critical one.

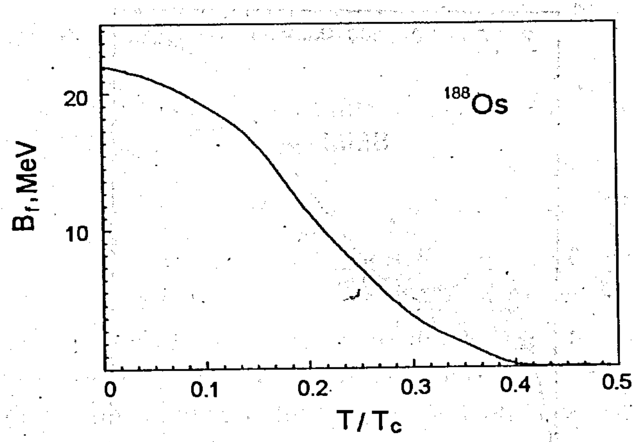

Fig. 3. Temperature dependence of the liquid drop fission barrier for ^{188}Os.

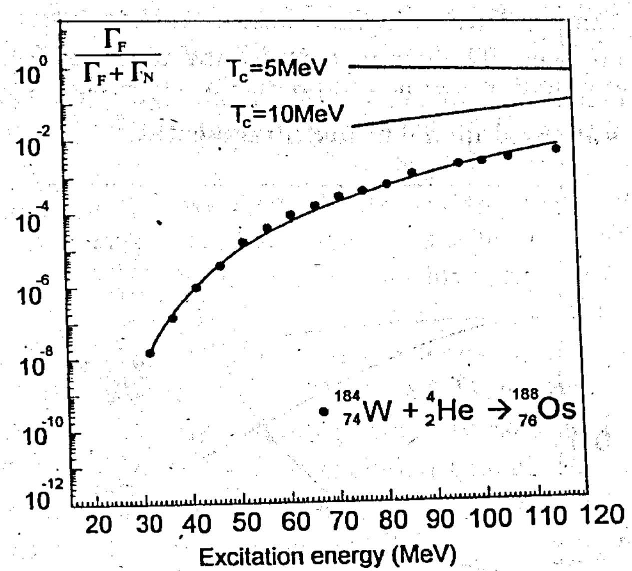

Fig. 4. Fission probabilities for ^{188}Os. The experimental data are from [15]. The upper lines are calculated for $T_c = 5$ MeV and 10 MeV.

Conclusion

The experimental data on fission probabilities for medium-heavy nuclei contradict the idea that the critical temperature for the liquid-gas phase transition (when the surface tension vanishes) is lower than 10 MeV. The caloric curve obtained by the ALADIN group can be conventionally explained in the framework of the Copenhagen statistical model of multifragmentation. The line in Fig. 1 is calculated in [16] for a nucleus with $A_\circ = 100$, assuming $T_c = 16$ MeV. The plateau-like behaviour is associated with the onset of the multifragmentation. At the crack temperature $T^* = 5 - 6$ MeV there exists a transition from the compound nucleus to the multidrop ensemble. In [16] it is called the cracking-phase transition, when energy is needed for increasing the surface of the system, while at higher excitation energy it is deposited into translation motion of the fragments. (Another proper term for that is the "liquid-fog" transition.) The second plateau, predicted by the model at $T = 11$ MeV, corresponds to the transition to the gas phase consisting of light nuclei with $A \leq 4$. But in fact this transition is masked by the intense secondary evaporation from the excited fragments even at the significantly lower temperatures.

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