Metastability and Boiling up of Asymmetric Nuclear Matter

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We study the process of boiling up (cavitation) in an asymmetric nuclear matter. The necessary condition for boiling is the equilibrium between the liquid and the saturated vapor phases. However, the boiling as a process means also the generation and the growth of the vapor phase (vapor bubbles) inside the liquid phase as a result of the heterophase fluctuations. In fact, the boiling can start in a metastable phase (overheated or extended liquid) only. If the pressure P_0 and the temperature T_0 provide a saturation of the vapor phase in the case of plane liquid-vapor boundary surface, the generation of the critical vapor bubbles of radius R_{crit}, which are in a thermodynamical equilibrium with the liquid, starts at higher temperature $T = T_0 + \Delta T$. The corresponding equilibrium condition for the chemical potentials in an asymmetric nuclear matter reads

$$\mu_q^{liq}\ (P_0 -)P, T_0, +)T, X_{\rm liq}) =$$
$$\mu_q^{vap}\ (P_{0,} T_0 +)T, X_{vap}), \qquad (1)$$

where μ_q is the chemical potential of the nucleon (q=n for neutron and q=p for proton), X is the asymmetry parameter defined as

$$X = (\rho_n - \rho_p)/(\rho_n + \rho_p),$$

ρ_n and ρ_p are the neutron and proton densities, respectively. The indices "liq" and "vap" in Eq. (1) denote the liquid and vapor phases, respectively, and $\Delta P = 2\sigma / R$ is the capillary pressure due to the vapor bubble of radius R where σ is the surface tension coefficient. A solution to Eq. (1) allows us to obtain the critical radius R_{crit} of the vapor bubble as a function of the overheating temperature ΔT for fixed values of P_0 and X_{liq}.

Using the temperature dependent Thomas-Fermi approximation [1] and a Skyrme-type force as the effective nucleon-nucleon interaction, we have solved the equilibrium equations (1) numerically. The dependence of the critical radius R_{crit} on the overheating temperature ΔT for pressure P_0 = 0.01 MeV/fm^3 and asymmetry parameters $X_{liq} = 0$, $X_{liq} = 0.1$ and $X_{liq} = 0.2$ is presented in Fig. 1 (we have used here and below $\sigma = 0.9$ MeV/fm^2). We point out the increase of the critical radius R_{crit} with the asymmetry parameters X_{liq}.

This is mainly due to the increase of the boiling temperature T_0 with the decrease of asymmetry parameter (see Ref. [1]).

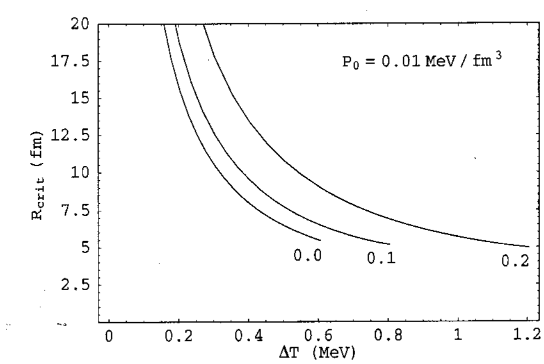

Figure 1: Temperature dependence of the critical radius R_{crit} for three cases of the asymmetry parameter *X=0, X=0.1, and X=0.2.*

The generation of the vapor bubble of arbitrary radius R is subsidized by a variation of the free energy $\Delta F(R)$ which is given by

$$\Delta F(R) = 4\pi\sigma(R^2 - \frac{2R^3}{3R_{crit}}). \qquad (2)$$

Figure 2 shows the dependence of the free energy $\Delta F(R)$ on the vapor bubble radius R for certain values of parameters T_0=5.8 MeV,)T = 1.2 MeV, and $X_{liq} = 0.2$. The maximum of $\Delta F(R)$ is located at $R = R_{crit}$ and its position is shifted to smaller values of R_{crit} with an increase of the overheating temperature)T. The bubble radius R_{crit} is the critical point for the metastable phase in the following sense: to start the boiling up, i.e., to start the infinite growth of size of the bubbles, the system must pass through the barrier of $\Delta F(R)$ to reach the region of $R > R_{crit}$.

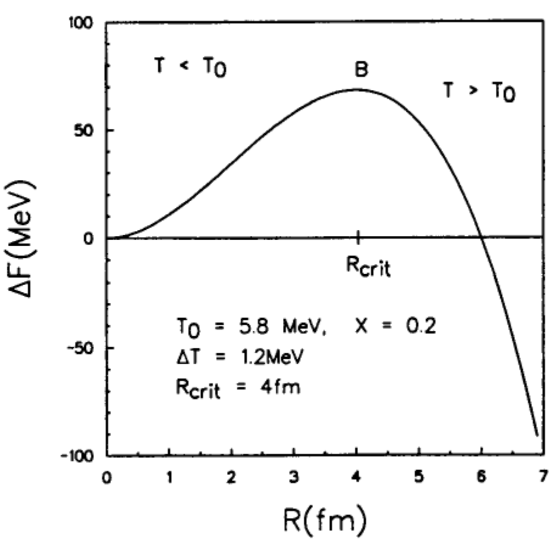

Figure 2: Dependence of the variation of free energy)$F(R)$ of metastable liquid on the radius R of the vapor bubble.

To evaluate the time evolution of the bubble radius R beyond the barrier at $R > R_{crit}$, one needs to know the equation of motion for the collective variable $R(t)$. We have studied this problem using the kinetic approach to the nuclear Fermi liquid [2]. Starting from the collisional kinetic equation, we have derived the following non-Markovian equation of motion for $R(t)$ without restrictions on the amplitude of $\Delta R = R(t) - R_{crit}$:

$$B\ddot{R} + \frac{\partial B}{\partial R}\ddot{R}^2 +$$
$$\int_{t_0}^{t} \dot{R}(t')\exp(\frac{t'-t}{\tau})\kappa(t,t') = -\frac{\partial \Delta F}{\partial R}, \qquad (3)$$

where $B \equiv B(R)$ is the mass coefficient, ϑ is the relaxation time and $\kappa(t,t')$ is the memory kernel. We have evaluated both transport coefficients $B(R)$ and $\kappa(t,t')$ assuming an irrotational motion of the Fermi liquid and taking into account the Fermi-surface distortion effects. Near the top of the barrier ΔF, the solution to Eq. (3) takes the following general form

$$\Delta R = C_\zeta e^{\zeta t} + A_\omega e^{-\Gamma t/2\hbar}\sin(Et/\hbar) +$$
$$B_\omega e^{-\Gamma t/2\hbar}\cos(Et/\hbar), \qquad (4)$$

The form of ΔR given by Eq. (4) means that the growth of bubble size is accompanied by the characteristic oscillations of radius R. These oscillations are due to the memory integral in Eq. (3). The characteristic energy, E, the damping parameter, Γ, and the instability growth rate parameter, ζ, depend on the relaxation time ϑ and the critical radius R_{crit}. In Fig. 3 we show the dependence of the instability growth rate parameter ζ, the energy of eigenvibrations, E, and the damping parameter,

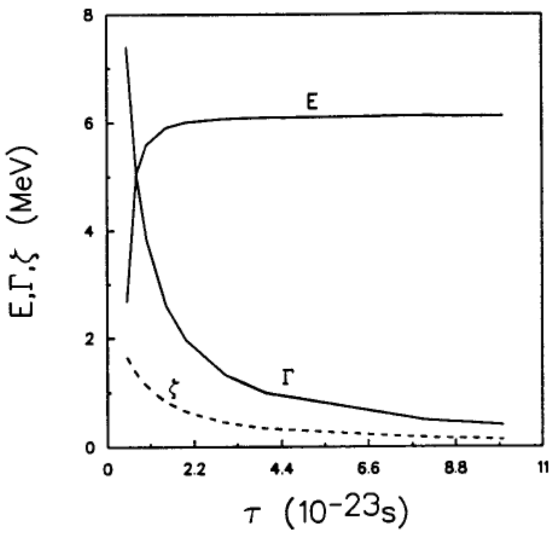

Figure 3: Dependence upon relaxation time τ of the characteristic energy E and width Γ of oscillations (solid lines) and the instability growth rate parameter ζ (dashed line).

э, on the relaxation time ϑ. The critical radius $R_{crit} = 4\text{fm}$ was taken the same as in Fig. 2. As seen from Fig. 3, the characteristic oscillations disappear in the short collision regime $\tau \to 0$, where the collective motion becomes Markovian. We point out that both the eigenenergy E and the damping parameter э depend on the temperature T_0. This fact can be used for an independent detection of the first order phase transition temperature T_0 in hot nuclei.

References

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