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Subcritical states of asymmetric nuclear matter

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Subcritical states of asymmetric nuclear matter

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Caloric curves measurements [1] provide important information on equation of state and liquid-vapor phase transition in nuclear matter. The plateau region of the caloric curve, that is, the dependence of temperature, T , on excitation energy per particle ε_{ex} , gives the signal of phase transition [2]. This flat region of the caloric curve is accompanied by an increase of energy fluctuations and demonstrates departure from the Fermi-gas-like equation of state. On the base of statistical mechanics it is possible to find signatures of liquid-vapor phase transition also for finite nuclear systems composed of a limited number of neutrons N and protons Z (small systems). Below we consider caloric curves for small nuclear systems and energy fluctuations for thermodynamic states along these curves. Calculations were performed at subcritical (i.e. below critical) values of temperature T and pressure P using formalism of Isothermal-Isobaric Ensemble.

The partition sum and the thermodynamic potential G (Gibbs free energy) for the system driven by the corresponding environmental variables are written as,

$$\Delta(N, Z, P, T) = \sum_V \exp[(-PV - F(N, Z, V, T))/T], \quad G = -T \ln(\Delta)$$

Here, summation (integration) is carried out over volume V , $F = F(N, Z, V, T)$ stands for the free energy of small nuclear system

Fermi free energy per particle $\phi_{TF}(\rho_n, \rho_p, T)$ [2] as $F = A\phi_{TF}(\rho_n, \rho_p, T)$, where $\rho_n = N/V$ and $\rho_p = Z/V$ are, respectively, the neutron and proton densities. In order to account for situation that system can be found in two-phase thermodynamic state (liquid + vapor) the partition sum yields $\Delta(N, Z, P, T) = \sum_{N^{liq} + N^{vap} = N, Z^{liq} + Z^{vap} = Z} \exp[(-P(V^{liq} + V^{vap}) - F^{liq} - F^{vap})/T]$

where $F^{liq} = F(N^{liq}, Z^{liq}, V^{liq}, T)$, $F^{vap} = F(N^{vap}, Z^{vap}, V^{vap}, T)$, and superscripts "liq" and "vap" denote the liquid and vapor phases, respectively. The partition sum takes the account of particles redistributed between liquid and vapor phases provided the total number of neutrons and protons are fixed. The average value of energy, $\langle E \rangle$, and its dispersion (the energy fluctuation σ_E squared), $\sigma_E^2 = \langle E^2 \rangle - \langle E \rangle^2$, are obtained from Gibbs free energy $G = -T \ln(\Delta)$ as $\langle E \rangle = G - T \frac{\partial G}{\partial T} - P \frac{\partial G}{\partial P}$, $\langle E^2 \rangle - \langle E \rangle^2 = -T^3 \frac{\partial^2 G}{\partial T^2} - 2PT^2 \frac{\partial^2 G}{\partial P \partial T} - P^2 T \frac{\partial^2 G}{\partial P^2}$

The excitation energy per particle ε_{ex} , needed for the determination of the caloric curve, $T(\varepsilon_{ex})$, is obtained as $\varepsilon_{ex} = (\langle E \rangle - E_{gs})/A$

where E_{gs} is the ground state energy at $T = 0$ and fixed value of P . We have calculated the isobaric caloric curves, using $P = 0.05 \text{ MeV}/\text{fm}^3$, for several small nuclear systems having different particle numbers $A = 48, 120$, and 216 at the same asymmetry parameter $X = (N - Z)/A = 1/6$. By the neutron-proton composition these systems correspond to ^{48}Ca , ^{120}Sn , and ^{216}Th nuclei. Calculation was carried out for the temperature interval $T = 5 \div 12 \text{ MeV}$ using KDE0v1 Skyrme nucleon-nucleon interaction [3]. The results for $A = 48, 120$, and 216 are shown in Fig. 1 by the dash-dotted, dashed, and dotted lines, respectively. With the aim of comparison, the calculation at the same pressure and asymmetry parameter was carried out for infinite asymmetric nuclear matter (solid line in Fig. 1). Comparing the dot-dashed, dashed and dotted lines with the solid one in Fig. 1 it is seen that the temperature in the middle of plateau region for the small systems is lower than that for infinite matter. Also, the results obtained for small systems are smooth and do not demonstrate fracture (derivative discontinuity) which is seen for infinite matter at bubble and dew points shown in Fig. 1 by arrows. We also obtained the energy dispersion $\sigma_E^2 = \langle E^2 \rangle - \langle E \rangle^2$ by means of Eq. (3). The calculation of the dispersion and, consequently, the fluctuation of energy requires the values of second derivatives of the Gibbs thermodynamic potential G with respect to the temperature and pressure. Figure 2 presents the energy dispersions for small nuclear systems with $A = 48, 120$, and 216 as functions of excitation energy per particle along the corresponding caloric curves shown in Fig. 1. Figure 2 demonstrates the increase of energy dispersions in the two-phase region of excitation energies between bubble and dew points. Such an increase, together with the plateau region in caloric curve $T(\varepsilon_{ex})$, gives the signature of the occurring phase transition. The presented results for small nuclear systems could be valuable to give an idea on the excitation energy range where to expect the observation of liquid-vapor phase transition (see Fig. 1 and Fig. 2 in the

attached materials).
Fig. 1. Isobaric caloric curves $T(\varepsilon_{\text{ex}})$ obtained at pressure $P = 0.05 \text{ MeV}/\text{fm}^3$ and neutron-proton asymmetry parameter $X = 1/6$. Dot-dashed, dashed, and dotted lines present the results for small nuclear systems with $A = 48, 120, \text{ and } 216$, respectively. Solid line gives the result in the case of infinite matter. The positions of bubble and dew points of infinite matter are shown by arrows. Calculations were carried out using KDE0v1 Skyrme nucleon-nucleon interaction [3].
Fig. 2. The energy dispersion per particle over square of temperature versus the excitation energy per nucleon ε_{ex} , see Eqs. (3), and (4). Results are obtained for small nuclear systems with $A = 48$ (dot-dashed line), 120 (dashed line), and 216 (dotted line) along the corresponding caloric curves, see Fig. 1. The range of ε_{ex} between bubble and dew points (vertical dashed lines) corresponds to coexistence of liquid and vapour phases for the case of infinite nuclear matter.

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