Nuclear symmetry energy effects on liquid-gas phase transition in hot asymmetric nuclear matter

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The liquid-gas phase transition in hot asymmetric nuclear matter is investigated within the relativistic mean-field model using the density dependence of nuclear symmetry energy constrained from the measured neutron skin thickness of finite nuclei. We find symmetry energy has a significant influence on several features of liquid-gas phase transition: the boundary and area of the liquid-gas coexistence region, the maximal isospin asymmetry, and the critical values of pressure and isospin asymmetry, all of which systematically increase with increasing softness in the density dependence of symmetry energy. The critical temperature below which the liquid-gas mixed phase exists is found higher for a softer symmetry energy.

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I. INTRODUCTION

The possible occurrence of liquid-gas phase (LGP) transition in intermediate energy heavy-ion collisions using neutron-rich stable and future radioactive beams provides a rather unique tool to probe hot and dense phases of highly asymmetric nuclear matter. Collision experiments [1,2] with stable heavy nuclei at intermediate energy indicate theoretically predicted [3] features of liquid-gas phase transition where the hot and compressed nucleus produced expands and fragments into several intermediate mass fragments (high-density liquid phase) and light particles and nucleons (low-density gas phase).

The early theoretical studies of the thermodynamic properties of liquid-gas phase transition [4–7] are mostly confined to symmetric nuclear matter that employed the quite well predicted [8–10] behavior of the symmetric nuclear matter equation of state (EOS). One of the major ingredients in studies of asymmetric nuclear matter require knowledge of the density dependence of symmetry energy $E_{\rm sym}(\rho)$ [11–13]. Unfortunately, the model predictions of $E_{\rm sym}(\rho)$ even for nuclear matter at zero temperature are extremely diverse [14]. Only at the nuclear saturation density $\rho_0 \approx 0.16\,{\rm fm}^{-3}$ the value of $E(\rho_0, T = 0) = 32 \pm 4$ MeV has been well constrained.

Recently some progress has been achieved by consistently constraining the symmetry energy of cold neutron-rich matter near normal matter density from analysis of isospin diffusion [11–13] and isoscaling [15] data in intermediate energy heavy-ion collisions and from the study of neutron skin thickness of several nuclei [16,17]. While knowledge of symmetry energy $E_{\rm sym}(\rho, T)$ at finite temperature in particular has received little attention [18–20] that is crucial for a proper understanding of the features of LGP transition in hot asymmetric nuclear matter. In fact, new qualitative features are expected when an asymmetric nuclear system with two conserved charges, baryon number and third component of isospin, undergoes a LGP change which has been suggested to be of second order [21]. Most previous studies of LGP transition [21–23] relied on model predictions of symmetry energy $E_{\rm sym}(\rho, T)$ with no or minimal contact with the available experimental data. Thus to understand better the features of LGP transition in hot asymmetric nuclear matter, it is imperative to employ the asymmetric nuclear EOS that has been constrained from analysis of skin thickness data of several nuclei [17] or from isospin diffusion/scaling data [12,20]. Such an investigation is particularly useful as future experiments with radioactive ion beams with large neutron-proton asymmetries can be used to explore [24,25] symmetry energy effects on liquid-gas phase transition.

In this article, we study the effects of constrained symmetry energy [17] on the thermodynamic properties of LGP in hot neutron-rich nuclear matter within relativistic mean-field (RMF) models [26].

The paper is organized as follows. In Sec. II we introduce the extended RMF model and describe the treatment of the liquid-gas coexistence phase. In Sec. III the numerical results for matter at finite temperature and density are presented. Section IV summarizes the results.

II. FORMALISM

We use two accurately calibrated models: NL3 [27] and FSUGold [28], that were obtained by fitting the model parameters to certain ground-state properties of finite nuclei. The interaction Lagrangian density in the nonlinear RMF model is given by [17,25]

$$\begin{aligned}\mathcal{L} = \overline{\psi}\left[g_s\phi - \left(g_v V_\mu + \frac{g_\rho}{2}\tau\cdot\mathbf{b}_\mu + \frac{e}{2}(1+\tau_3)A_\mu\right)\gamma^\mu\right]\psi \\ - \frac{\kappa}{3!}(g_s\phi)^3 - \frac{\lambda}{4!}(g_s\phi)^4 + \frac{\zeta}{4!}g_v^4(V_\mu V^\mu)^2 \\ + \Lambda_v\left(g_\rho^2\mathbf{b}_\mu\cdot\mathbf{b}^\mu\right)\left(g_v^2 V_\mu V^\mu\right), \qquad (1)\end{aligned}$$

which includes a isospin doublet nucleon field (ψ) interacting via exchange of isoscalar-scalar σ (ϕ), isoscalar-vector ω (V^μ), isovector-vector ρ ($\mathbf{b}^\mu$) meson fields, and the photon (A^μ) field. The nonlinear σ meson couplings (κ, λ) soften the symmetric nuclear matter EOS at around ρ_0, while its high density part is softened by the self-interactions (ζ) for the ω meson field.

For the original NL3 set with $\zeta = \Lambda_v = 0$, the saturation of symmetric nuclear matter occurs at a Fermi momentum of $k_F = 1.30\ {\rm fm}^{-1}$ with a binding energy $B/A \approx 16.3$ MeV and an incompressibility of $K_0 = 271$ MeV. The original FSUGold [28], with two additional couplings $\zeta = 0.06$ and

$\Lambda_v = 0.03$, with $K_0 = 230$ MeV produces a soft symmetric and asymmetric nuclear matter EOS. To study the effect of symmetric nuclear EOS (e.g., incompressibility K_0) on the symmetry energy, the original NL3 Lagrangian has been extended [17,25] to include the isovector coupling Λ_v which is then varied along with g_ρ in both NL3 and FSUGold to generate various $E_{\rm sym}(\rho)$. All combinations of Λ_v and g_ρ are adjusted to a constant $E_{\rm sym}(\overline{\rho}, T = 0) = 25.67$ (26.00) for the NL3 (FSUGold) at an average density $\overline{\rho}$ corresponding to $k_F = 1.15$ fm^{-1} where the total binding energy of ^{208}Pb is reproduced within 4 MeV. Thus the additional coupling provides an efficient way to change in a controlled manner the density dependence of nuclear symmetry energy without compromising the success of the model. However, note that NL3 overbind superheavy nuclei by ∼7 MeV [29] while for FSUGold the overbound for ^{208}Pb is by ∼4 MeV [28].

The model parameter set (Λ_v, g_ρ) is then varied to explore $E_{\rm sym}(\rho)$ effects on the liquid-gas phase transition in hot asymmetric nuclear matter. For the present study we use $\Lambda_v = 0.0$–0.03 since the resulting symmetry energies and their slopes and curvatures are in reasonable agreement with that extracted from neutron skin thickness of several nuclei as well as the isoscaling and isospin diffusion data [17]. In particular, all these data can be simultaneously reproduced [17] with $\Lambda_v = 0.02$–0.03. It may be also noted that with increasing Λ_v the density dependence of symmetry energy becomes softer in both the NL3 and FSUGold models [17]. While at a finite Λ_v the symmetry energy $E_{\rm sym}(\rho, T = 0)$ is found to be particularly stiff in FSUGold than in the NL3 parameter set at densities $\rho \gtrsim \rho_0$.

At finite temperature and density the energy density $\mathcal{E}$ can be readily obtained from the thermodynamical potential Ω [21] as

$$\mathcal{E} = \frac{2}{(2\pi)^3} \sum_{q=n,p} \int d^3k\, E^*(k)([n_q(k)]_+ + [n_q(k)]_-) + \frac{m_s^2\phi^2}{2} + \frac{\kappa}{3!}(g_s\phi)^3 + \frac{\lambda}{4!}(g_s\phi)^4 + \frac{m_v^2 V_0^2}{2} + \frac{\zeta}{8}(g_v V_0)^4 + \frac{m_\rho^2 b_0^2}{2} + 3\Lambda_v (g_v V_0)^2 (g_\rho b_0)^2, \quad (2)$$

where $E^*(k) = \sqrt{k^2 + m^{*2}}$ is the effective energy. The distribution function for nucleon and antinucleon (referred to as ± sign) is as usual [21–23]

$$[n_q(k)]_\pm = \frac{1}{\exp[(E^*(k) \mp \nu_q)/T] + 1} \quad (q = n, p), \quad (3)$$

where the effective chemical potential for neutron and proton is expressed as $\nu_q = \mu_q - g_v V_0 \pm g_\rho b_0/2$. The chemical potentials can be determined from the conserved baryon and isospin densities:

$$\rho = \frac{2}{(2\pi)^3} \int d^3k\, (G_p(k) + G_n(k)), \quad (4)$$

$$\rho_3 = \frac{2}{(2\pi)^3} \int d^3k\, (G_p(k) - G_n(k)), \quad (5)$$

where $G_q(k) = [n_q(k)]_+ - [n_q(k)]_-$.

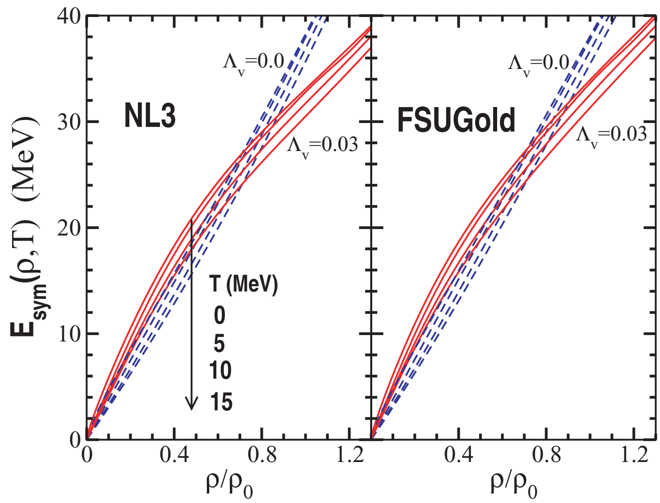

FIG. 1. (Color online) Density dependence of nuclear symmetry energy at temperatures $T = 0, 5, 10, 15$ MeV in NL3 and FSUGold sets with couplings $\Lambda_v = 0.0$ and 0.03.

As in the zero temperature case, several model studies [12,19,30,31] have indicated that the EOS for hot neutron-rich nuclear matter can be expressed in the parabolic form:

$$E(\rho, T, \alpha) = E(\rho, T, \alpha = 0) + E_{\rm sym}(\rho, T)\alpha^2 + \mathcal{O}(\alpha^4), \quad (6)$$

where the neutron-proton asymmetry is $\alpha = (\rho_n - \rho_p)/\rho$. The (ρ, T) dependence of symmetry energy can be estimated from $E_{\rm sym}(\rho, T) \approx E(\rho, T, \alpha = 1) - E(\rho, T, \alpha = 0)$. Figure 1 shows the density dependence of nuclear symmetry energy at $T = 0, 5, 10, 15$ MeV in the NL3 and FSUGold sets. For all choices of Λ_v the symmetry energy decreases with increasing temperature especially at small densities $\rho \lesssim \rho_0$ that is entirely due to the decrease in the kinetic energy contribution. For $\Lambda_v = 0.0$ (0.03) the density dependence of $E_{\rm sym}(\rho, T)$ at all temperatures exhibits a systematic trend of small (large) value at subsaturation densities and a large (small) value at supranormal densities resulting in an overall stiffer (softer) asymmetric nuclear matter EOS. Moreover, at a finite Λ_v, a stiff (soft) symmetric nuclear EOS for NL3 (FSUGold) with large (small) incompressibility K_0 systematically gives a soft (stiff) $E_{\rm sym}(\rho, T)$ at $\rho \gtrsim \rho_0$ [17].

III. RESULTS

The above-described models can now be used to study LGP in hot asymmetric nuclear matter. The system is stable against LGP separation if its free energy F is lower than the coexisting liquid (L) and gas (G) phases, i.e., $F(T, \rho) < (1 - \lambda)F^L(T, \rho^L) + \lambda F^G(T, \rho^G)$ with $\rho = (1 - \lambda)\rho^L + \lambda\rho^G$, where $0 < \lambda < 1$ and $\lambda = V^G/V$ being the fraction of the total volume occupied by the gas phase. The stability condition implies the inequalities [21]:

$$\rho \left(\frac{\partial P}{\partial \rho}\right)_{T,\alpha} > 0, \quad (7)$$

$$\left(\frac{\partial \mu_p}{\partial \alpha}\right)_{T,P} < 0 \quad \text{or} \quad \left(\frac{\partial \mu_n}{\partial \alpha}\right)_{T,P} > 0. \quad (8)$$

The first inequality indicates mechanical stability which means a system at positive isothermal compressibility remains stable at all densities. The second inequality stems from chemical instability which shows that energy is required to change the concentration in a stable system while maintaining temperature and pressure fixed. If one of these conditions get violated, a system with two phases is energetically favorable. The two phase coexistence is governed by the Gibbs's criteria for equal pressures and chemical potentials in the two phases with different densities but at the same temperature:

$$P(T, \rho^L) = P(T, \rho^G), \tag{9}$$

$$\mu_q(T, \rho^L) = \mu_q(T, \rho^G)(q = n, p). \tag{10}$$

Figure 2 shows the pressure as a function of nucleon density at a fixed temperature $T = 10$ MeV with different values of asymmetry α in the *original* NL3 and FSUGold sets. Below a critical value of asymmetry α, the pressure is seen (dotted curves) to decrease with increasing density resulting in negative incompressibility and thereby a mechanically unstable system. The stable two-phase (liquid-gas) configuration at each density is obtained from Maxwell construction (solid lines). Analogs to intermediate energy heavy-ion collisions [1,2] when the hot matter in the high density (liquid) phase expands it enters the coexistence LGP where the pressure decreases at a fixed $\alpha \neq 0$ for the two-component asymmetric matter. Whereas, for symmetric nuclear matter at $\alpha = 0$ the pressure remains constant at all densities. Finally, the system leaves the coexistence region and vaporizes into the low density (gas) phase. Of particular interest here is the symmetry energy effects on the isotherms. It is clearly seen that in contrast to the original NL3 with $\Lambda_v = 0$, the softer $E_{\rm sym}(\rho)$ in the original FSUGold with $\Lambda_v = 0.03$ [17] (see Fig. 1) enforces

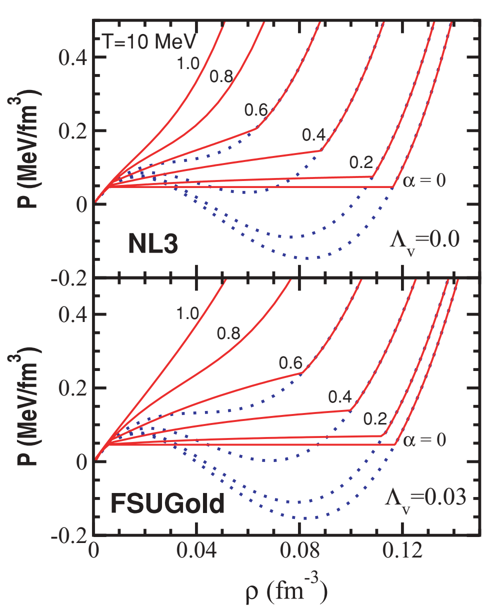

FIG. 2. (Color online) Pressure as a function of density at temperature $T = 10$ MeV for various isospin asymmetry α in the original NL3 set [27] with $\Lambda_v = 0.0$ and in the original FSUGold set [28] with $\Lambda_v = 0.03$. The dotted curves refer to unstable single phase while the solid curves refer to stable matter; see text for details.

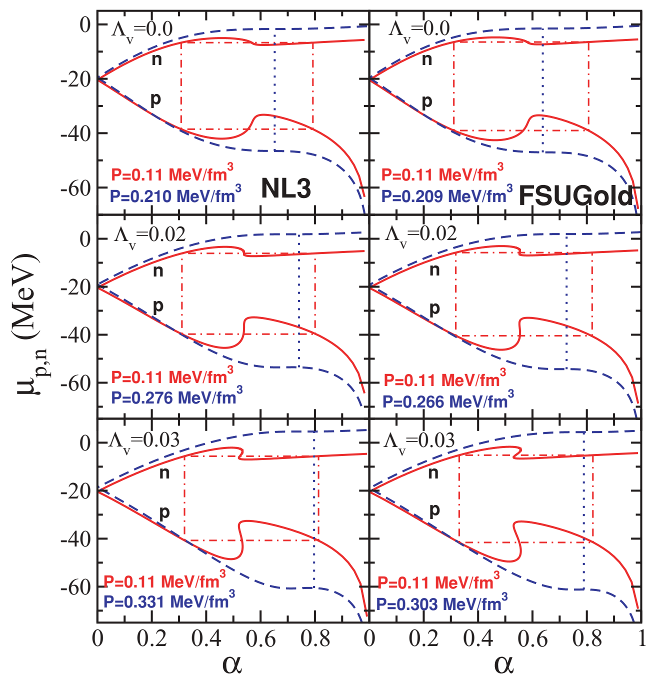

FIG. 3. (Color online) Chemical potential isobars as a function of isospin asymmetry α at temperature $T = 10$ MeV in NL3 and FSUGold sets with different Λ_v couplings. The geometrical construction used to obtain the isospin asymmetries and chemical potentials in the two coexisting phases is also shown.

the onset of pure liquid phase to a higher density resulting in a wider coexistence region for each asymmetry α. Moreover, the critical pressure P_c above which the mixed liquid-gas phase vanishes is seen larger for this soft FSUGold set; a detailed discussion of which is presented below.

The details of chemical evolution for the LGP transition is depicted in Fig. 3 where the neutron and proton chemical potentials are shown as a function of isospin asymmetry α at a fixed $T = 10$ MeV and pressure $P = 0.11$ MeV/fm^3 for the NL3 and FSUGold at various Λ_v values. As usual, the bare nucleon mass has been subtracted from the chemical potentials. At fixed pressure and Λ_v, the solutions of the Gibbs conditions (9) and (10) for phase equilibrium form the edges of a rectangle and can be found by geometrical construction as shown in Fig. 3. At each Λ_v, the two different values of α defines the high-density liquid-phase boundary [with small $\alpha = \alpha_1(T, P)$] and the low-density gas-phase boundary [with large $\alpha = \alpha_2(T, P)$]. From the figure it is evident that the symmetry energy dependence of Λ_v in NL3 and FSUGold [17,25] leads to different phase boundaries $\alpha_1(T, P)$ and $\alpha_2(T, P)$ and hence should predict different thermodynamic properties for the LGP transition.

As the pressure increases the system encounters a critical pressure P_c beyond which the matter is stable but below which the second inequality (8) gets violated and the system becomes chemically unstable. The critical pressure P_c is determined by the inflection point $(\partial\mu/\partial\alpha)_{T,P_c} = (\partial^2\mu/\partial\alpha^2)_{T,P_c} = 0$. The disappearance of chemical instability at P_c results in the neutron (proton) chemical potential to decrease (increase) with decreasing asymmetry α. Figure 3 also shows the chemical potential isobars at the critical pressure (dashed lines). The rectangle from Gibbs condition then collapses into a vertical line at $\alpha \equiv \alpha_c$. Correspondingly, (P_c, α_c) defines the critical point at a given temperature that refers to the upper boundary of instability with respect to pressure variation. Note at $T = 10$ MeV, the critical values (P_c, α_c) at $\Lambda_v = 0.0, 0.02, 0.03$ are respectively at (0.210, 0.652), (0.276, 0.741), (0.331, 0.797) for the NL3 set and at (0.209, 0.638), (0.266, 0.725), (0.303, 0.789) for the FSUGold set. Interestingly, we also find at a finite temperature the stiffness of symmetry energy has a significant influence on the phase-separation boundaries of LGP transition [20]. In general, an overall softer symmetry energy (larger Λ_v) that corresponds to a stiffer E_{sym} at subsaturation densities gives systematically larger critical pressure and an enhanced asymmetry in the system. Moreover at a finite α, the overall softer symmetry energy $E_{\mathrm{sym}}(\rho, T)$ in the NL3 compared to FSUGold [17] translates to a larger critical pressures and asymmetry for the LGP transition.

All the pairs of solutions of Gibbs conditions, $\alpha_1(T, P)$ and $\alpha_2(T, P)$, form the phase-separation boundary or the binodal surface. In Fig. 4 we show the section of the binodal surface under isothermal compression of asymmetric nuclear matter at $T = 10$ MeV in the NL3 and FSUGold sets. As expected the point of equal concentration (EC) corresponding to symmetric nuclear matter is independent of Λ_v. The critical point (CP) and EC divide the binodal section into two branches. One branch is the high-density (liquid) phase that is less asymmetric while the other branch corresponds to the more asymmetric low-density (gas) phase. Thus the matter on the left (right) of the binodal surface represents stable liquid (gas) phase. It is clearly seen here that the critical point (P_c, α_c) depends on the density dependence of the symmetry energy associated with different Λ_v values.

We also indicate on the binodal surface the maximal isospin asymmetry (MA), α_{MA}, of the system. Thus more neutron-rich matter on the right side of the surface when compressed/expanded at fixed α will never encounter a coexistence phase. Note here the maximal asymmetry is also quite sensitive to Λ_v, i.e., on $E_{\mathrm{sym}}(\rho, T)$. Such effects found in the present study should have strong influence on the experimentally observed isospin distillation phenomena [32] where the gas phase is more neutron rich (large n/p ratio) compared to the more symmetric liquid phase. For pressure $P \geqslant 0.10$ MeV/fm^3 the magnitude of isospin distillation is more sensitive to the symmetry energy used. However, this may be difficult to access experimentally.

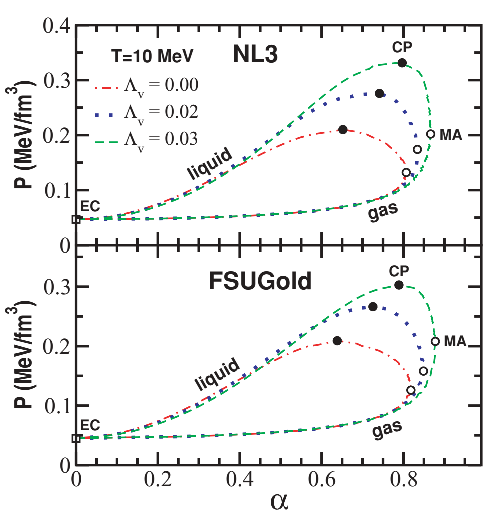

FIG. 4. (Color online) The section of binodal surface at temperature $T = 10$ MeV in NL3 and FSUGold sets with different Λ_v couplings. The critical point (CP), the point of equal concentration (EC), and the maximal asymmetry (MA) are indicated.

IV. SUMMARY AND CONCLUSIONS

A new feature for LGP transition in asymmetric system, referred to as retrograde condensation [21], arises when a nucleon gas prepared at an asymmetry $\alpha_c < \alpha < \alpha_{\mathrm{MA}}$ is compressed at fixed total α. The matter remains mechanically stable but chemically unstable. Thus a coexisting liquid phase emerges which finally vanishes when the system leaves the binodal surface as a pure gas. As the extent $\Delta\alpha = \alpha_{\mathrm{MA}} - \alpha_c$ is found to decrease for softer symmetry energy with higher Λ_v, the possibility of such unique-phase condensation phenomena also becomes minimal.

The present study clearly suggests that for liquid-gas phase transition in hot asymmetric nuclear matter, the critical values of pressure and isospin asymmetry, the maximal asymmetry and the area and shape of the binodal surface are quite sensitive to the density dependence of symmetry energy. Consistently larger values of these thermodynamic variables stem from overall softer symmetry energies which give higher values of E_{sym} at low densities that are relevant for the construction of the binodal curve.

The existence of critical isospin asymmetry parameter α_c at a given temperature indicates that for $\alpha > \alpha_c$ the system will not change completely into the liquid phase. Conversely, this suggests that at a fixed α there exists a critical temperature T_c beyond which the system can only be in the gas phase at all pressures. In Fig. 5(a) we present T_c as a function of α in the FSUGold set for different couplings Λ_v. For symmetric nuclear matter ($\alpha = 0$), the critical temperature

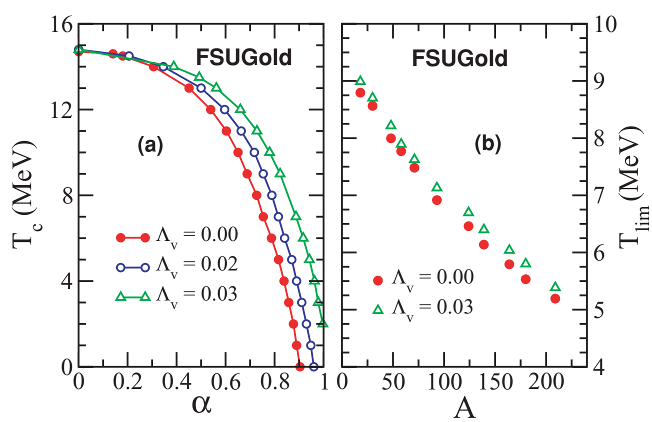

FIG. 5. (Color online) (a) Critical temperature T_c versus isospin asymmetry α and (b) limiting temperature T_{lim} versus mass number A of finite nuclei for different Λ_v in the FSUGold set.

for LGP transition in this model is $T_c = 14.7$ MeV. With increasing asymmetry $\alpha \gtrsim 0.6$, T_c decreases rapidly. A softer density dependence in symmetry energy (larger Λ_v) shows the coexisting liquid-gas phase can prevail for larger values of T_c. We find that for the soft symmetry energy ($\Lambda_v = 0.03$) even pure neutron matter ($\alpha = 1$) can exhibit LGP transition at $T \leqslant T_c = 2$ MeV. While the stiffest symmetry energy ($\Lambda_v = 0$) at $\alpha > 0.9$ predicts that the matter can only be in the pure gas phase at all temperatures.

The limiting temperature, $T_{\rm lim}$, attained by a finite nucleus due to Coulomb instability toward liquid-gas phase transition can be obtained by considering the hot nucleus in equilibrium with the surrounding nucleon gas [33,34]. The two-phase Gibbs conditions, Eqs. (9)–(10), then become [23,33]

$$\begin{aligned} P(T,\rho^L,\alpha^L) + P_{\rm Cou}(\rho^L) + P_{\rm sur}(T,\rho^L) &= P(T,\rho^G,\alpha^G),\\ \mu_n(T,\rho^L,\alpha^L) &= \mu_n(T,\rho^G,\alpha^G),\\ \mu_p(T,\rho^L,\alpha^L) + \mu_C(\rho^L) &= \mu_p(T,\rho^G,\alpha^G). \end{aligned} \tag{11}$$

For a uniformly charged spherical nucleus of mass and charge (A, Z) and radius R, the Coulomb contribution to the proton chemical potential and pressure are $\mu_{\rm Cou} = 6Ze^2/(5R)$ and $P_{\rm Cou}(\rho) = Z^2e^2\rho/(5AR)$. The surface pressure on the nucleus is $P_{\rm sur} = -2\gamma(T)/R$, where the surface tension is taken as [35] $\gamma(T) = (1.14\ {\rm MeV\ fm}^{-2})(1 + 3T/2T_c)(1 - T/T_c)^{3/2}$. Here T_c is the critical temperature for infinite symmetric nuclear matter. In Fig. 5(b) the limiting temperature for β-stable finite nuclei is found to decrease monotonically with A. As in T_c, a softer $E_{\rm sym}(\rho)$ leads to somewhat larger values of $T_{\rm lim}$. This may suggest that for a hot finite nucleus undergoing liquid-gas phase transition to lighter nuclei and nucleons, the symmetry energy effects on the binodal surface could survive. This can only be estimated in models that include fluctuations and correlations in the fragmenting nucleus which is beyond the scope of the present study.

In summary the effects of isospin symmetry interaction on the liquid-gas phase transition in hot neutron-rich nuclear matter is investigated. For this we have used the two accurately calibrated relativistic mean-field models, the NL3 [27] and the FSUGold [28], wherein the density dependence of nuclear symmetry energy at zero temperature has been constrained within a limited range by neutron skin thickness data of several atomic nuclei. We find considerable sensitivity of the symmetry energy on the features of phase transition even for the limited symmetry energy range corresponding to $\Lambda_v \simeq 0.02$–0.03 that reproduces the skin and/or the isospin diffusion/scaling data [17]. Thus the present study suggests that precise information on the density dependence of symmetry energy may be obtained from analysis of observables related to liquid-gas phase transition in future experiments with exotic beams. In particular, we find overall softer symmetry energies give progressively larger phase-separation boundaries with higher critical values for pressure and isospin asymmetry as well as maximal asymmetries. At a given asymmetry we find the critical temperature for the existence of the mixed liquid-gas phase increases with softer symmetry energy and predicts the possible occurrence of even an unstable pure neutron matter at finite temperatures.

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