Stability condition in hot symmetric nuclear matter

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Introduction

The first order liquid-gas phase transition in nuclear matter near nuclear density is of huge importance not only in context to astrophysical relevance but also in the heavy-ion collision experiments. It forms a prominent feature in the crust of neutron star where density and temperature are relatively low as compared to the core [1].

The liquid-gas phase transition in the nuclear matter is analogous to liquid-gas phase transition in water. The isotherms are typical Van der Waals type. Here an attempt is made to study the stability condition of these isotherms at low density for symmetric nuclear matter (SNM) using effective field theory motivated relativistic mean field (E-RMF) formulation.

Formulation and Force Parameter

The Equation of State (EoS) is calculated using the E-RMF Theory [2]. It is an elegant gauge theory for describing the interaction among hadrons and is thermodynamically consistent. The newly developed IOPB-I force parameter is used here to study the mechanical and thermal stability of nuclear matter at low density. The IOPB-I set describes properties like neutron skin thickness, charge radius very well and is known to reproduce the higher limit of neutron star mass [3]. The versatility of this set is therefore explored here in the finite temperature regime.

The symmetric nuclear matter (SNM) is a two-component system where the system is composed of an equal number of protons and neutrons. Since Coulomb interaction is hypothetically zero in SNM, the system is reduced to a simple one-component system. The intrinsic stability of such a system (one component of single-phase) requires that

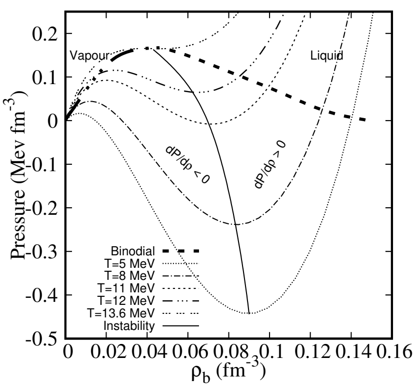

FIG. 1: The pressure isotherm together with the phase diagram showing binodial and instability boundary for the set IOPB-I.

$$\left(\frac{\partial S}{\partial T}\right)_\rho > 0, \left(\frac{\partial P}{\partial \rho}\right)_T > 0, \quad (1)$$

where the first condition corresponds to dynamical stability and the second one ensures mechanical stability. The Gibb's condition for two-phase to coexist in equilibrium (for one component system) is given by [4]

$$T_1 = T_2, P_1 = P_2, \mu_1 = \mu_2, \quad (2)$$

where 1 and 2 refer to the first and second phase, respectively.

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Results and Discussions

Fig. 1 shows the phase diagram where the pressure isotherms are plotted as a function of density at various temperature along with the phase coexistence (binodial) and instability boundary. One can see that, for each small positive pressure, there are three values of the density. At first, the pressure for SNM at finite temperature should be positive due to the thermal and Fermi degeneracy pressure. As density increases slightly, the attractive force increases which try to reduce the volume of the system and pressure goes from positive to negative. This phase violates one of the stability condition in Eq. 1 i.e. mechanical stability. This represents the phase separation process. The system has no alternative but to split into separate phases in equilibrium. Although, phase separation may occur even when the one-phase system is stable. This is called the metastable state [5]. As density is further increased, the repulsive force becomes stronger and it again drives pressure to positive values.

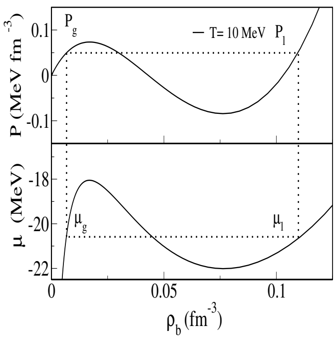

FIG. 2: The graphical solution of the two phase coexistence at T= 10 MeV for set IOPB-I

The phase coexistence boundary is determined by satisfying the set of the condition given in Eq. 2. The graphical representation of one such solution is shown in Fig. 2. This solution determines the boundary of binodial shown in Fig. 1. Not every isotherm have a solution of Eq. 2 at small positive pressure. For such temperatures, the nuclear matter exists only in one stable phase (liquid phase), and there is a mixture of the liquid and gas phases in thermodynamic instability. This happens at T = 8-10 MeV. After this temperature, phase transition starts taking place and liquid and vapour remain in phase coexistence. At zero temperature, zero density vapour is in coexistence with saturation density liquid. The two-phase coexistence can occur unless one observes an inflation point in the isotherm where $\frac{\partial P}{\partial \rho} = \frac{\partial^2 P}{\partial \rho^2} = 0$. For this case, i.e. IOPB-I set, this occurs at 13.6 MeV. After this temperature, nuclear matter exists in the vapour phase only.

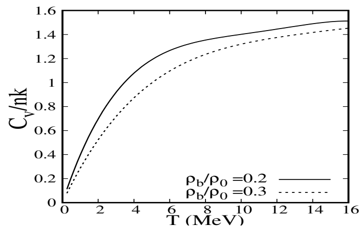

FIG. 3: Specific heat for symmetric nuclear matter for the set IOPB-I

The dynamical stability requires $C_v > 0$. This is shown in Fig. 3 where specific heat at constant density is plotted as a function of temperature. The specific heat approaches zero as the temperatures vanishes, as the change in entropy approaches zero for T=0. On the other hand, at higher temperatures, the specific heat asymptotically approaches the noninteracting limit $\frac{3nK}{2}$. The degree of convergence to this limit depends essentially on the global density.

References

[1] N. Sandulescu, Phys. Rev. C **70** (2004) 025801.

[2] R. J. Furnstahl *et al.*, Nucl. Phys. A **615** (1997) 441.

[3] B. Kumar *et al.*, Phys. Rev. C **97** (2018) 045806.

[4] A. Carbone *et al.*, Phys. Rev. C **83** (2011) 024308.

[5] M. Abd-Alla *et al.*, Phys. Rev. C **36** (1987) 4.