Critical parameters of liquid-gas phase transition in symmetric nuclear matter

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Introduction

The liquid-gas phase transition (LGPT) in the nuclear matter in the low-density regime is the canonical example of phase transition. Critical properties corresponding to this phase transition provide vital information on the underlying nucleon-nucleon (NN) interactions. Therefore, it becomes essential to examine nuclear matter properties as a function of density, pressure, temperature, and neutron-proton asymmetry etc. The main aim of heavy-ion induced dynamics is to validate the phase transformation phenomenon on the theoretical as well as the experimental front.

LGPT in the nuclear matter is a first-order phase transition, where two-phases i.e. more ordered liquid and less ordered gaseous phase remain in phase coexistence until a temperature T_c is reached, above which the system remains in the gaseous phase only. This point corresponds to the inflation point in the phase diagram.

There have been numerous calculations both within the relativistic and non-relativistic domain to calculate the related parameters such as temperature, pressure and density etc. theoretically. The literature suggests the critical temperature in the range of ≈ 14-16 MeV [1]. Here an attempt has been made to estimate these critical parameters within effective field theory motivated relativistic mean field theory (E-RMF). A newly developed force parameter IOPB-I [3] is used realizing its vitality in the zero-temperature limit for both finite nuclei and infinite nuclear matter.

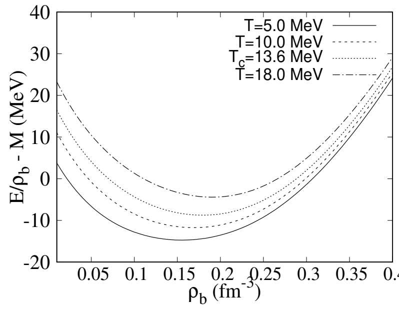

FIG. 1: The binding energy as a function of baryon density ρ_b at various temperatures for the IOPB-I set.

Formalism

In the E-RMF theory, mesons are collectively taken as fields and describe the interaction among nucleons [2]. The most significant advantage of E-RMF is that it is thermodynamically consistent and follows the relevant virial theorem. Therefore, it is straightforward to extrapolate this theory in the finite temperature regime. To do this, one must have a thermodynamic function of the system which is ensemble average of operators arising in theory. Here baryon and antibaryon occupation numbers are defined by the Fermi-Dirac distribution function. The energy and pressure are then determined using the Stress Energy tensor $T_{\mu\nu}$.

Results and Discussions

In the symmetric nuclear matter where proton fraction is y_p=0.5, meson corresponding to asymmetry in density and mass, i.e. ρ and

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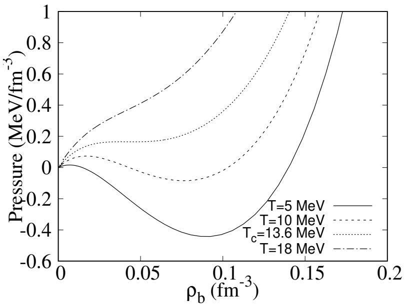

FIG. 2: The pressure versus baryon density ρ_b at various temperatures for the IOPB-I set.

δ do not arise. The only relevant couplings are due to the scalar σ and vector ω fields and their self (k_3, k_4,ζ_0) and cross-couplings (η_1,η_2). These couplings define extra density dependence on scalar and vector potential. Now with the liquid-gas phase transition analogy, one expects that binding energy should decrease with increase in temperature. This is shown in Fig. 1 where binding energy per nucleon obtained as a function of baryon density is shown at different temperatures.

It is apparent that the system tends to become less bound as one increases the temperature and the binding energy keeps decreasing with temperature. The curves around saturation become flat, which signify the softness of equation of state (EoS) at low density. The nuclear saturation density starts increasing with temperature.

In a liquid-gas phase diagram, the phase transition is characterised by a non-continuous transition between the two states. This is termed as the first order phase transition, and in general, such phase transition involves the latent heat. Similarly, the nuclear matter undergoes a first order phase transition. The system remains in two-phase coexistence unless a critical temperature is reached after which the system can only exist in the gaseous phase. This transition is marked by an inflation point which is given by [4]

$$\frac{\partial p}{\partial \rho} = \frac{\partial^2 p}{\partial \rho^2} = 0. \qquad (1)$$

The Fig. 2 shows the onset of the liquid-gas phase transition where the pressure is plotted as a function of baryon density for the IOPB-I set. There is a very nice pocket at low temperature signifying the two-phase coexistence which vanishes after the critical temperature T_c is reached. The corresponding pressure and density are termed as critical pressure P_c and critical density ρ_c. The estimated values of these critical parameters in IOPB-I framework are given in Table I. The corresponding experimental and theoretical (relativistic) numbers are also displaced.

	T_c (MeV)	P_c (MeV/fm^3)	ρ_c (fm^{-3})
IOPB-I	13.60	0.1627	0.048
Experiment [1]	17.9 ± 0.4	0.31 ± 0.07	0.06 ± 0.01
Theoretical [5]	14-16	0.16-0.43	0.04-0.07

TABLE I: The calculated critical parameters using IOPB-I force for symmetric nuclear matter.

Generally, the force parameters with high incompressibility produce higher value of critical temperature and pressure [1]. These parameters can not be used for EoS calculation due to their stiffness and they tend to predict high neutron star mass. Other RMF sets in their present form predict the critical temperature in the range of 14-16 MeV. Our calculation predicts it 13.6 MeV for IOPB-I set. These sets behave differently due to their different vector self-coupling (ζ_0) term, which plays a significant role in determining EoS at finite temperature.

References

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