Instabilities in hot asymmetric nuclear matter and the density dependence of symmetry energy

N. Alam[1],* H. Pais[2], C. Providência[2], and B. K. Agrawal[1]
[1]*Saha Institute of Nuclear Physics, HBNI, Kolkata - 700064, India.*
[2]*CFisUC, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal.*

Hot asymmetric nuclear matter plays an essential role in the dynamics of core-collapse supernova. During collapse the matter can reach up to temperature 20 MeV and density $1.5-2.0$ times the normal nuclear density ($\rho_0 \sim 0.16$ fm^{-3}). This density and temperature range includes both the homogeneous and inhomogeneous phase of matter. For density well below ρ_0, matter become inhomogeneous and light and heavy nuclear clusters are formed. Existence of such inhomogeneities modifies the neutrino transport, which will affect the formation of shock wave, cooling of proto-neutron star. It also influences the crustal properties of neutron stars. Thus, study of the instabilities, which determines this inhomogeneous phase, is crucial for core-collapse simulations and obtaining the crustal properties of neutron stars.

In this contribution, we have calculated the spinodal instabilities for various temperature using relativistic mean field (RMF) nuclear models. We have also analysed the sensitivity of critical parameters of asymmetric nuclear matter to the symmetry energy slope L, and for this purpose, different variants of RMF model having different values of L have been constructed by varying the strength of σ-ρ and ω-ρ cross couplings of mesons.

We have used thermodynamical spinodal method to determine boundary of the instability region and critical points. In this method, nuclear matter constituted by protons and neutrons is stable with respect to separation into two phase if the free energy density $\mathcal{F}$ of the system is a convex function of neutron and proton number density, ρ_n and ρ_p, respectively. Stability conditions for asymmetric nuclear matter impose that the curvature matrix of the free energy density

$$\mathcal{C}_{ij} = \left(\frac{\partial^2 \mathcal{F}}{\partial \rho_i \partial \rho_j}\right)_T, \qquad (1)$$

is positive [1]. The stability conditions take the form

$$\mathrm{Tr}(\mathcal{C}) > 0 \quad \text{and} \quad \mathrm{Det}(\mathcal{C}) > 0, \qquad (2)$$

Here, the free energy $\mathcal{F}$ of the system is obtained within the RMF framework.

*Electronic address: naosad.alam@saha.ac.in

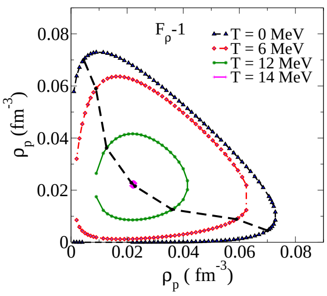

FIG. 1: Temperature dependence of the spinodal zone computed for $F_\rho 1$ model.

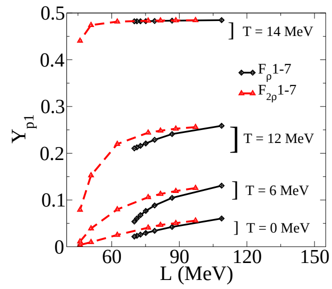

FIG. 2: Critical proton fraction as a function of L, for different temperatures, for F_ρ and $F_{2\rho}$ families.

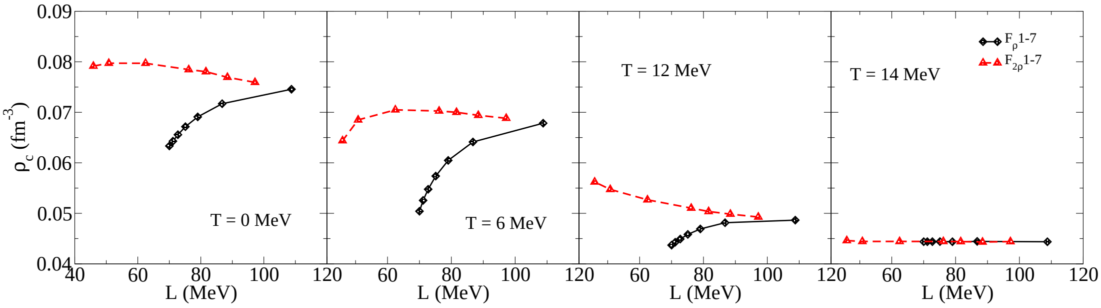

FIG. 3: Critical density as a function of L, for different temperatures, for F_ρ and $F_{2\rho}$ families.

We will also calculate the critical points for each temperature T, which are important to define under which conditions the system is expected to be clusterized. These points satisfy simultaneously

$$\mathrm{Det}(\mathcal{C}) = 0 \quad (3)$$
$$\mathrm{Det}(\mathcal{M}) = 0, \quad (4)$$

with

$$\mathcal{M} = \begin{pmatrix} \mathcal{C}_{11} & \mathcal{C}_{12} \\ \frac{\partial|\mathcal{C}|}{\partial\rho_p} & \frac{\partial|\mathcal{C}|}{\partial\rho_n} \end{pmatrix}. \quad (5)$$

In this work, we have considered two different families of RMF models, namely, F_ρ and $F_{2\rho}$ [2]. F_ρ family includes mixing term of the σ and ρ mesons ($\sigma\rho^2$), whereas $F_{2\rho}$ includes mixing term of the ω and ρ mesons ($\omega^2\rho^2$). Each family contains seven different models ($F_\rho 1 - F_\rho 7$ and $F_{2\rho}1 - F_{2\rho}7$) with different values of L, which are obtained by varying the strength of cross coupling $\sigma\rho^2$ (for F_ρ family) and $\omega^2\rho^2$ (for $F_{2\rho}$ family).

We have determined the region of instability by calculating the spinodal surface in the (ρ_p, ρ_n) space. Fig. 1 shows the spindal instability domains of $F_\rho 1$ parameterization for temperatures T = 0, 6, 12 and 14 MeV. The dashed line represents the line of critical points. The area of spinodal section decreases with the increase in temperature, which is found to be similar to the one obtained in Ref. [3]. At critical temperature the section reduce to a point, beyond which homogeneous matter is always stable.

In Fig. 2 , the critical proton fractions, y_p, for neutron rich matter are displayed as a function of L for different temperatures and, for both the families of models considered. The critical proton fraction increases with L irrespective of temperature. At lower values of L, there is a notable difference in y_p across F_ρ and $F_{2\rho}$ families, except for $T = 14$ MeV case, where this difference vanishes. This difference also disappears as the values of L increases.

Now, we are going to discuss how the critical density, ρ_c, changes with L and T. In Fig. 3, the critical densities are plotted as a function of L for the different models and temperatures considered. The critical density is always increases with L for F_ρ family, but the same is not true for $F_{2\rho}$ family. $F_{2\rho}$ family shows this trend for the lowest temperatures considered, 0 and 6 MeV, and $L \lesssim 60$ MeV. In all other cases, ρ_c decreases when L increases. This different behaviour across the families originates due to their different cross coupling terms which govern the density dependence of symmetry energy.

In summary, we have found that the instability region in the (ρ_n, ρ_p) space decreases with the increase of temperature. Critical parameters of asymmetric matter, y_p and ρ_c, depend strongly on the symmetry energy elements. They are relatively more sensitive to L at low temperatures, which tend to wash out with increasing temperature.

References

[1] N. Alam, H. Pais, C. Providência, and B. K. Agrawal, Phys. Rev. C, **95**, 055808 (2017).
[2] N. Alam, A. Sulaksono, and B. K. Agrawal, Phys. Rev. C, **92**, 015804 (2015).
[3] S. S. Avancini, L. Brito, Ph. Chomaz, D. P. Menezes, and C. Providência **74**, 024317 (2006).