Finite Range Effective Interactions and Temperature dependence of Nuclear Symmetry Energy

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Introduction

The behaviour of nuclear symmetry energy $E_s(\rho)$ at suprasaturation densities is very essential for the understanding of many phenomena in astrophysics . At saturation density ρ_0, it accounts for the energy required per nucleon to convert protons into neutrons in symmetric nuclear matter. It controls the proton fraction in neutron stars. Since nuclear symmetry energy forms an important part of nuclear equation of state, its accurate determination, both at subnormal and suprasaturation densities, will put ample light on the equation of state of asymmetric nuclear matter. The density dependence of $E_s(\rho)$ is not yet well determined, particularly, at densities much higher than the saturation point ρ_0. There is no experimental evidence (from terrestrial laboratories) about the density dependence of $E_s(\rho)$ at these densities. In order to get a reasonable description of high density behaviour of $E_s(\rho)$, often, we are forced to extrapolate theories well suited and tested around saturation density. It is worth to mention here that, the extrapolated results of $E_s(\rho)$ at high densities from different theoretical models are extremely divergent and even contradicting. However, there have been many attempts in recent times to constrain the nuclear symmetry energy at sub normal densities from the analyses of finite nuclei [1, 2], neutron skin thickness [3], resonance and excitations [4, 5]. Even though these analyses have significantly improved our knowledge; we are yet to reach at a satisfactory level of understanding of nuclear symmetry snergy [6].

The temperature dependence of nuclear symmetry energy has become a subject of current research interest because of its role in the studies of isoscaling analyses of Heavy Ion reactions and the formation mechanism of neutron stars particularly the properties of proto neutron stars (PNS). While the temperature dependence of the kinetic part of the nuclear symmetry energy is well understood, the temperature dependence of its interaction part is not yet known to a satisfactory extent.

In the present work, we have investigated the temperature dependence of nuclear symmetry energy using some finite range effective interactions proposed in some earlier works.

Formalism

The finite range effective interaction proposed earlier [7, 8] with a Yukawa form for the finite range part reads as

$$\begin{aligned} v(\mathbf{r}) &= t_0(1+x_0P_\sigma)\delta(\mathbf{r}) \qquad (1)\\ &+ \frac{1}{6}t_3(1+x_3P_\sigma)\left[\frac{\rho(\mathbf{R})}{1+b\rho(\mathbf{R})}\right]^\gamma \delta(\mathbf{r}) \\ &+ (W+BP_\sigma-HP_\tau-MP_\sigma P_\tau)\,\frac{e^{-r/\alpha}}{r/\alpha}. \end{aligned}$$

$t_0, t_3, x_0, x_3, b, \gamma, W, B, H, M, \alpha$ are the interaction parameters which are fitted from different properties of symmetric nuclear matter and finite nuclei. The finite range effective interactions in the above equation has already been successfully used for the calculation of bulk properties of nuclear matter, properties of finite nuclei, neutron star masses and proton radioactivity.

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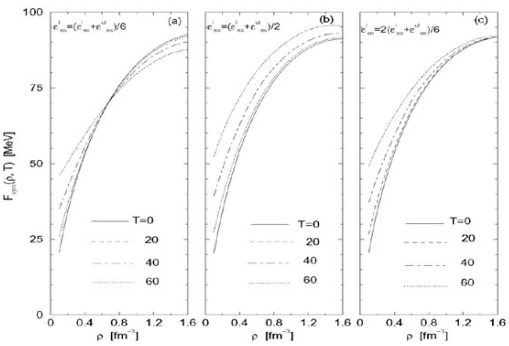

FIG. 1: Free symmetry energy shown as a function of density at temperatures T=0, 20, 40 and 60 MeV for three representative neutron-proton effective mass splitting.

In the present work, we focussed on the calculation of the free symmetry energy

$$F_{sym}(\rho, T) = F_{pnm}(\rho, T) - F_{snm}(\rho, T), \quad (2)$$

where, $F_{pnm}(\rho, T)$ and $F_{snm}(\rho, T)$ are respectively the free energy of pure neutron matter and symmetric nuclear matter. $F_{pnm}(\rho, T)$ and $F_{snm}(\rho, T)$ are calculated from their respective energy densities and entropy densities:

$$F_{snm}(\rho, T) = \frac{1}{\rho}\left[H_0(\rho, T) - TS_0(\rho, T)\right] \quad (3)$$

$$F_{pnm}(\rho, T) = \frac{1}{\rho}\left[H_n(\rho, T) - TS_n(\rho, T)\right] \quad (4)$$

Results and Discussion

The temperature dependence of free symmetry energy using the finite range effective interactions is plotted as a function of density in figure 1 for representative temperatures. It is evident from the figure that, at a given density, the free symmetry energy increases with the increase in temperature. However, the temperature dependence of free symmetry energy is not that much visible for small changes in temperature i.e. from 0-10 MeV. The increment in free symmetry energy with temperature depends on the magnitude of neutron-proton effective mass splitting in neutron rich matter and density. If the neutron-proton effective mass splitting is zero (curves of Fig 1(b)), i.e, for equal neutron and proton effective mass, the increment is almost uniform all over the density range considered. For an increase in neutron-proton effective mass splitting, the increment slows down for higher densities making a room for a reversal at certain density(visible at a lower density in Fig 1(a)). It should be emphasised here that, momentum dependent effective interactions or finite range effective interactions are required for a simulation of neutron-proton effective mass splitting which have a direct role in the high temperature behaviour of nuclear symmetry energy. Although, the sign of the neutron-proton effective mass is questionable, in the present work, we have considered a positive value of this quantity for the calculation of nuclear symmetry energy and free symmetry energy based upon the prediction by a host of microscopic calculations.

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