Temperature dependence of symmetry energy

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Introduction

The fact that the equation of state (EoS) of nuclear matter contains a symmetry energy term is known since very early days of nuclear physics but the properties of the EoS due to differing neutron (ρ_n) and proton (ρ_p) number densities remain more elusive to date. The best possible means of studying experimentally the nuclear EoS at subnormal density is through heavy-ion reactions because in this kind of reaction, an excited nucleus (the composite of projectile and target nuclei) expands to a subnuclear density and disintegrates into various light and heavy fragments in a process called multifragmentation. The isospin effects observed in these reactions are believed to be a probe for the nuclear symmetry energy (NSE) and its density dependence [1], studies of which are not only important in the context of nuclear physics but also for the astrophysical processes such as neutron stars [2] and supernova explosions.

Theoretical Formalism

The energy per nucleon of nuclear matter at finite temperature is given by

$$\epsilon(\rho, X, T) = \epsilon^{kin}(\rho, X, T) + \epsilon^{pot}(\rho, X, T) \quad (1)$$
$$= \frac{1}{\rho}\sum_{\tau}\int \frac{p^2}{2m_\tau} f_\tau(\vec{r},\vec{p})d^3p + \frac{\rho J_v C[1-\beta\rho^{\frac{2}{3}}]}{2}$$

where J_v=$J_{v00} + X^2 J_{v01}$, J_{v00} and J_{v01} represent the volume integrals of the isoscalar t_{00}^{M3Y} and isovector t_{01}^{M3Y} components of M3Y interaction respectively, isospin asymmetry X=$\frac{\rho_n-\rho_p}{\rho_n+\rho_p}$, ρ_n+ρ_p=ρ and τ stands for n or p. The DDM3Y effective interaction is given by $v_{0i}(s, \rho, \epsilon^{kin})$=$t_{0i}^{M3Y}(s, \epsilon^{kin})g(\rho)$ for i=0,1 and the values of the constants C, β of the density dependence $g(\rho)$=$C(1-\beta\rho^{\frac{2}{3}})$ of the effective interaction are obtained by reproducing the saturation energy per nucleon and the saturation density ρ_0 of symmetric nuclear matter (SNM). The NSE $E_{sym}(\rho)$=$\epsilon(\rho, 1, T) - \epsilon(\rho, 0, T)$ represents a penalty levied on the system as it departs from the symmetric limit of ρ_n=ρ_p. At temperature T, the phase-space distribution function is given by Fermi-Dirac distribution

$$f_\tau(\vec{r},\vec{p}) = \frac{2}{h^3}\frac{1}{\exp[\frac{\frac{p^2}{2m_\tau}+U_\tau-\mu_\tau}{T}]+1} \quad (2)$$

where μ_τ are the chemical potentials determined from the constraint

$$\rho_\tau = \int f_\tau(\vec{r},\vec{p})d^3p \quad (3)$$

and U_τ are the single particle potentials which for this DDM3Y interaction are given by

$$U_n = \int g(\rho)[t_{00}^{M3Y} + t_{01}^{M3Y}X]\rho d^3r,$$
$$U_p = \int g(\rho)[t_{00}^{M3Y} - t_{01}^{M3Y}X]\rho d^3r. \quad (4)$$

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Calculations and Results

The calculation of ϵ^{kin} requires the distribution functions f_τ which in turn require the knowledge of U_τ and μ_τ and again these two quantites require the value of ϵ^{kin}. Thus, ϵ^{kin}, U_τ, μ_τ and f_τ are obtained in a self-consistent manner using the following steps: 1.First a particular set of values for ρ , X, T are chosen at which ϵ is to be calculated. Thus, chosen values of neutron and proton densities are

$$\rho_n = [1+X]\frac{\rho}{2}, \quad \rho_p = [1-X]\frac{\rho}{2}. \qquad (5)$$

2.An initial guess value of ϵ^{kin} is taken which, by choice, is the the zero temperature value of $\epsilon^{kin} = [\frac{3\hbar^2 k_F^2}{10m}]F(X)$. 3.Using this value of ϵ^{kin}, t_{0i}^{M3Y} are evaluated and then from this and the chosen value of ρ, $v_{0i}(s, \rho, \epsilon^{kin})$ are obtained. Using these values the single-nucleon potential U_τ are calculated using Eq.(4). 4.Now from these U_τ and suitably guessed chemical potentials μ_τ, the Fermi-Dirac distribution functions f_τ are calculated. 5.Using these f_τ, the densities ρ_τ are evaluated using Eq.(3). 6.Then μ_τ are slightly adjusted to match the calculated and the chosen values of ρ_τ and again f_τ are calculated. 7.This new f_τ functions are used to calculate ρ_τ again. To reduce the difference between this calculated and chosen ρ_τ, the μ_τ are accordingly adjusted until the conditions $|\frac{\text{calculated } \rho_\tau - \text{chosen } \rho_\tau}{\text{chosen } \rho_\tau}| \leq 10^{-5}$ are achieved. 8.This first iteration ϵ^{kin} value is then calculated using first term on the right hand side of Eq.(1) and the f_τ finalized in the above step (7) and used to calculate the single-nucleon potentials U_τ. 9.Again the process from step (3) is repeated. This process is continued until values obtained in nth and (n+1)th steps satisfy both the conditions $|\frac{U_\tau^{n+1} - U_\tau^n}{U_\tau^{n+1}}| \leq 10^{-5}$ and $|\frac{\epsilon_{n+1}^{kin} - \epsilon_n^{kin}}{\epsilon_{n+1}^{kin}}| \leq 10^{-5}$. Then the values of ϵ^{kin}, U_τ, f_τ in the (n+1)th step are taken as the final values. Then NSE $E_{sym}(\rho, T)$ is obtained using Eq.(1) and plotted in Fig.1. as functions of ρ/ρ_0 at different temperatures.

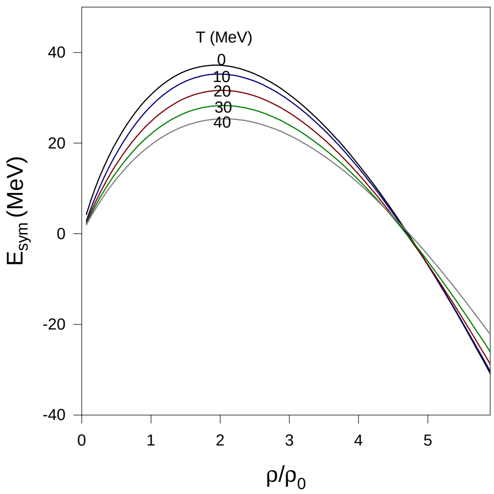

FIG. 1: $E_{sym}(\rho, T)$ as functions of ρ/ρ_0 at different temperatures.

Summary and Conclusion

The temperature dependence of the nuclear symmetry energy is investigated within a self-consistent thermal model using the isospin, energy and density dependent M3Y interaction. It is shown that the symmetry energy generally decreases with increasing temperature. The decrement of the symmetry energy with temperature is essentially due to the decrement of the potential energy part of the symmetry energy with temperature. The resulting density and temperature dependent symmetry energy can be used to estimate the average freeze-out density of the intermediate mass fragments.

Acknowledgments

The research work of P.R.C. is sponsored under Dr. D. S. Kothari postdoctoral program by UGC [No.F.4-2/2006(BSR)/13-224/2008(BSR)].

References

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