Incompressibility of asymmetric nuclear matter

S. Chakraborty[1], B. Sahoo[2*] and S. Sahoo[3]
[1]*Department of Physics, M. M. M. College, Durgapur, West Bengal, India.*
[2]*Department of Applied Sciences, DIATM, Durgapur, West Bengal, India.*
[3]*Department of Physics, National Institute of Technology, Durgapur, West Bengal, India.*
**E-mail: patra_babita@rediffmail.com*

The equation of state (EOS) of isospin asymmetric nuclear matter is a fundamental quantity that determines the properties of system as small and light as an atomic nucleus and as large and heavy as a neutron star. The EOS represents the binding energy per nucleon as a function of density. One of the nuclear matter properties which play an important role in the determination of EOS is the incompressibility that measures how quickly a curve changes direction. The energy per nucleon and incompressibility has been calculated as a function of density (ρ) for different asymmetry parameter (β) by using the finite range effective interaction [1]

$$V_{eff}(r) = t_0\left(1+x_0 P_\sigma\right)\delta\left(\vec{r}\right) + \frac{t_3}{6}\left(1+x_3 P_\sigma\right)\rho^\gamma(R)\delta\left(\vec{r}\right) + \left(W + B P_\sigma - H P_\tau - M P_\sigma P_\tau\right) f(r) \quad \text{-------(1)}$$

This form of effective interaction is very similar to Skyrme-type of interactions except for the fact that the t_1 and t_2 terms in the latter case have been replaced by the short-range interaction $\left(W + B P_\sigma - H P_\tau - M P_\sigma P_\tau\right) f(r)$, where the $f(r)$ can have any one of the conventional form such as Yukawa, Gaussian or exponential form.

The total energy per nucleon E(ρ) can be expressed analytically for the given effective interaction as

$$E(\rho) = \frac{3\hbar^2 k_f^2}{10m} + \frac{E_0}{2}\frac{\rho}{\rho_0} + \frac{E_\gamma}{(\gamma+2)}\left(\frac{\rho}{\rho_0}\right)^{(\gamma+1)} + \frac{E_{ex}}{2}\left(\frac{\rho}{\rho_0}\right) J(\rho) \quad \text{.......(2)}$$

where,

$$E_0 = \rho_0\left[\frac{3}{4}t_0 + \left(W + \frac{M}{4} - \frac{H}{2} + \frac{B}{2}\right)\right] \times \int f(r)\, d^3 r$$

$$E_\gamma = (\gamma+2)\frac{t_3}{16}\rho_0^{(\gamma+1)} ,$$

$$E_{ex} = \rho_0\left(M - \frac{W}{4} + \frac{H}{2} - \frac{B}{2}\right)\int f(r)\, d^3 r ,$$

For Yukawa form of interaction,

$$J(x) = \left(\frac{3}{32x^6} + \frac{9}{8x^4}\right) In\left(1+4x^2\right) - \frac{3}{8x^4} + \frac{9}{4x^2} - \frac{3}{x^3}\tan^{-1}(2x)$$

where $x = \frac{k_f}{\Lambda}$; $\Lambda = 2.386$ (approx.)

The total energy per nucleon in symmetric nuclear matter can be expanded upto 2nd order of density as

$$E(\rho) = E(\rho_0) + L_0\,\chi + \frac{K_0}{2}\chi^2 \quad \text{-------- (3)}$$

where $\chi = \frac{\rho - \rho_0}{3\rho_0}$ is a dimensionless characterizing variable, $L_0 = 3\rho_0\left[\frac{dE(\rho)}{d\rho}\right]\Big|_{\rho=\rho_0}$ and $K_0 = 9\rho_0\left[\frac{d^2E(\rho)}{d\rho^2}\right]\Big|_{\rho=\rho_0}$.

According to the definition of saturation density L_0 =0 and hence the 2^{nd} term should vanish.

$$E(\rho) = E(\rho_0) + \frac{K_0}{2}\chi^2 \text{ ------------ (4)}$$

It has also been found that the energy per nucleon in asymmetric nuclear matter has a simple quadratic dependence of β [2]:

$$E(\rho,\beta) = E(\rho,0) + E_{sym}(\rho)\,\beta^2, \text{ --------(5)}$$

where β= (ρ_n – ρ_p) / ρ is the asymmetry parameter. *E (ρ, β)* is plotted as a function of ρ for different asymmetry β in fig 1.

The symmetry energy describes how the energy of nuclear matter increases as the system departs from equal number of neutron (N) and proton (Z). Around the normal nuclear matter density ρ_0 the nuclear symmetry energy $E_{sym}(\rho)$ can be expanded upto 4^{th} order of χ as [3]:

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2}\chi^2 + \frac{J_{sym}}{6}\chi^3 + \frac{I_{sym}}{24}\chi^4 \text{ ,--------(6)}$$

where L, Ksym, Jsym ,Isym are slope parameter, curvature parameter, 3^{rd} and 4^{th} order co-efficient of nuclear symmetry energy at ρ_0. The incompressibility K can be obtained from binding energy per nucleon [3]. Considering only upto 2^{nd} order terms in β,

$$K(\rho,\beta) = 18\,\rho\,\frac{dE(\rho,\beta)}{d\rho} + 9\,\rho^2\,\frac{d^2E(\rho,\beta)}{d\rho^2} \text{ -----------(7)}$$

K (ρ, β) is plotted as a function of ρ for different asymmetry β in fig 2. Incompressibility decreases when β approaches 0.33.

References:

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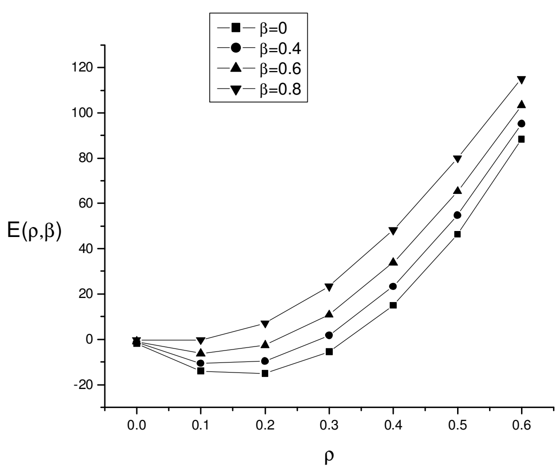

Fig:-1

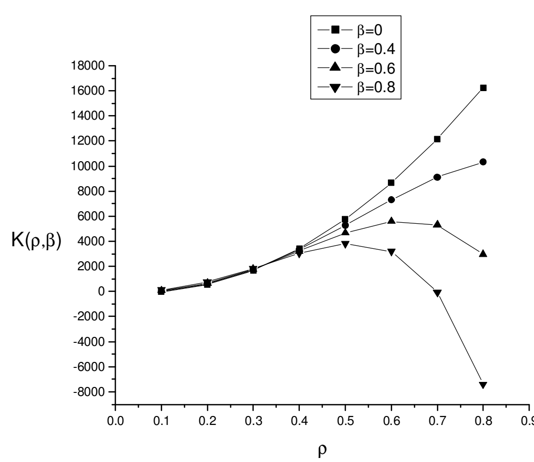

Fig:-2