Contribution of 2nd order and 4th order symmetry energy on proton fraction of β-stable neutron star matter

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Theoretically almost all many body theory calculations discussed in the literature so far revealed that second order nuclear symmetry energy $E_{sym,2}(\rho)$ positively characterizes the isospin dependent part of the equation of state (EOS) of asymmetric nuclear matter (ANM) and the 4th order symmetry energy $E_{sym,4}(\rho)$ is not so important for moderate values of densities [1]. It may be a good approximation to the EOS of ANM, but at the same time it may cause large errors when it is applied to determine some special conditions. For example, at supra normal densities the higher order terms can significantly modify the proton fraction of neutron stars in β - equilibrium [2–4].

To observe the contribution of 2nd order and 4th order symmetry energy on the EOS of ANM, we calculate the proton fraction $Y_p = \frac{\rho_p}{\rho}$ in β-stable neutron star matter by using simple parameterization of finite range effective interaction [5].

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

where $f(r)$ represents a short-range interaction of Yukawa form and is specified by a single range parameter Λ. The other symbols in equation (1) have their usual meanings.

The chemical composition is determined by the requirement of charge neutrality and $\beta-$ equilibrium. The charge neutrality requires that $\rho_p = \rho_e = \rho Y_p$. Below the muon threshold density $\left(\mu_e < m_\mu c^2 \approx 105.6\text{MeV}\right)$ the charge neutrality condition leads to the following relation [2, 6]

$$\mu_e = \mu_n - \mu_p \quad \text{----------------(2)}$$

$$c\hbar\left(3\pi^2 \rho Y_p\right)^{\frac{1}{3}} = 4\beta E_{sym,2}(\rho) + 8\beta^3 E_{sym,4}(\rho) \quad \text{----------------- (3)}$$

where $\beta = \frac{\rho_n - \rho_p}{\rho}$ is the asymmetry parameter.

As the baryon density exceeds the muon threshold density, where $\mu_e > m_\mu c^2 \approx 105.6\text{MeV}$ the electrons convert to negative muons. In this case the constituents of neutron stars are neutrons, protons, electrons and muons [7]. The chemical equilibrium condition for the $(npe\mu)$ system reads

$$\mu_e = \mu_\mu = \mu_n - \mu_p = 4\beta E_{sym,2}(\rho) + 8\beta^3 E_{sym,4}(\rho) \quad \text{------------------- (4)}$$

The charge neutrality condition can be written as,

$$3\pi^2 (c\hbar)^3 \rho Y_p - \mu_\mu^3 - \left[\mu_\mu^2 - (m_\mu c)^2\right]^{3/2} \theta(\mu_\mu - m_\mu) = 0$$

------------------ (5)

where $\theta(x)$ is the Heaviside step function [7].

The equilibrium proton fraction Y_p for (npe) and $(npe\mu)$ systems can now be derived by solving Eq. (3) and (5) respectively considering terms up to $E_{sym,2}(\rho)$ as well as up to $E_{sym,4}(\rho)$. The obtained proton fraction for β - equilibrium (npe) and $(npe\mu)$ neutron star matter is plotted as a function of density up to 2nd order symmetry energy $E_{sym,2}(\rho)$ and 4th order symmetry energy $E_{sym,4}(\rho)$ in Fig: (1) and (2). In the same Fig. the results obtained from FSU GOLD [2] is also shown for comparison. It is found that the proton fraction for $(npe\mu)$ neutron star matter is larger than that for the (npe) nuclear matter. Further it is seen that at high density $(=3\rho_0)$ for the term up to 4th order symmetry energy $E_{sym,4}(\rho)$ the proton fraction Y_p increases by 7.93% for exact (npe) matter and 7.14% for exact $(npe\mu)$ matter. These results indicate that the 4th order symmetry energy $E_{sym,4}(\rho)$ may have considerable effects on the proton fraction Y_p in β - stable $(npe\mu)$ neutron star matter. In other words the EOS of asymmetric nuclear matter including the term up to the 4th order symmetry energy could be a good approximation for the determination of the proton fraction in β - stable $(npe\mu)$ neutron star matter.

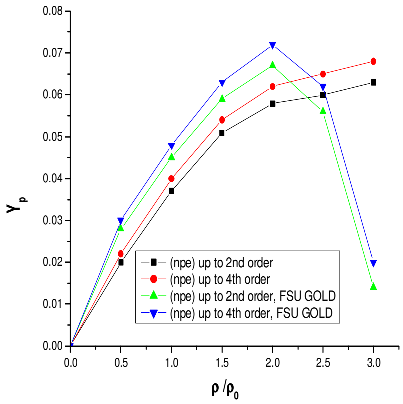

Fig: (1)

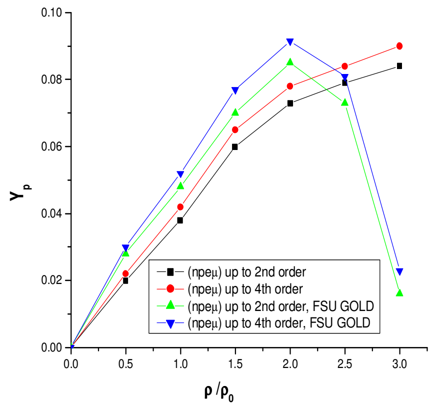

Fig: (2)

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