Effect of non-linear vector interactions in nuclear matter

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Introduction

The success of the relavistic mean-field theory in the description of finite nuclei and infinite nuclear matter and models of neutron star via the exchange of mesons (σ, ω & ρ) is well known [1]. However over last half decade with recent precise observation of high mass pulsars such as PSR J1614-2230 ($M = 1.97 \pm 0.04$) [2] and PSR J0348+0432 ($M = 2.01 \pm 0.04$) [3] has lead to serious considerations on the role nuclear interactions at high densities relevant to neutron stars. On one hand the models must satisfy the constraints on the symmetry energy parameters such as J and L at nuclear matter saturation density and on the other hand the heavy-ion collision data constraints at intermediate densities one has to satisfy the observed mass and properties of the pulsars. In the quest for acheiving a satisfactory microscopic theory for infinite nuclear matter obeying the aforesaid constraints, we include the effect of higher order vector interactions 'ω^4' in the non-linear chiral sigma model [4] and investigate the effect on the resulting equation of state at high densities.

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The Model

The modified lagrangian (including 'ω^4' interactions) for the present model is

$$\begin{aligned}\mathcal{L} &= \bar{\psi}\left[\left(i\gamma_\mu\partial^\mu - g_\omega\gamma_\mu\omega^\mu - \frac{1}{2}g_\rho\vec{\rho}_\mu\cdot\vec{\tau}\gamma^\mu\right) - g_\sigma\left(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi}\right)\right]\psi \\ &+\frac{1}{2}\left(\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi} + \partial_\mu\sigma\partial^\mu\sigma\right) - \frac{\lambda}{4}\left(x^2 - x_0^2\right)^2 - \frac{\lambda b}{6m^2}\left(x^2 - x_0^2\right)^3 - \frac{\lambda c}{8m^4}\left(x^2 - x_0^2\right)^4 \\ &-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}{g_\omega}^2x^2\omega_\mu\omega^\mu + \frac{\xi}{\mathbf{4!}}\mathbf{g}_\omega{}^\mathbf{4}\mathbf{x}^\mathbf{4}(\omega_\mu\omega^\mu)^\mathbf{2} - \frac{1}{4}\vec{R}_{\mu\nu}\cdot\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\cdot\vec{\rho}^\mu.\end{aligned}$$

As emphasized in our ealier work [4], the model parameters are sternly constrained because of the above mentioned relations. The inclusion of ω^4 interaction and parameter ξ in the model gives us some flexibility to tune the interactions and hence affect the overall energy and pressure of the many baryon system. The modified total energy density 'ε' and pressure 'P' of symmetric nuclear matter for a given baryon density is (in terms of $Y = m^*/m$):

$$\begin{aligned}\epsilon &= \frac{\gamma}{2\pi^2}\int_0^{k_F} k^2\sqrt{k^2+m^{*2}}dk + \frac{m^2}{8C_\sigma}(1-Y^2)^2 \\ &- \frac{b}{12C_\sigma C_\omega}(1-Y^2)^3 + \frac{c}{16m^2C_\sigma C_\omega^2}(1-Y^2)^4 \\ &+ \frac{1}{2}m_\omega^2\omega_0^2Y^2 + \frac{\xi}{4}m_\omega^4\omega_0^4Y^4 \\ p &= \frac{\gamma}{6\pi^2}\int_0^{k_F}\frac{k^4}{\sqrt{k^2+m^{*2}}}dk - \frac{m^2}{8C_\sigma}(1-Y^2)^2 \\ &+ \frac{b}{12C_\sigma C_\omega}(1-Y^2)^3 - \frac{c}{16m^2C_\sigma C_\omega^2}(1-Y^2)^4 \\ &+ \frac{1}{2}m_\omega^2\omega_0^2Y^2 + \frac{\xi}{4}m_\omega^4\omega_0^4Y^4\end{aligned}$$

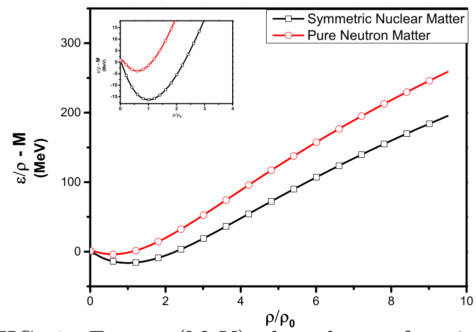

FIG. 1: Energy (MeV) plotted as a function of normalized baryon density.

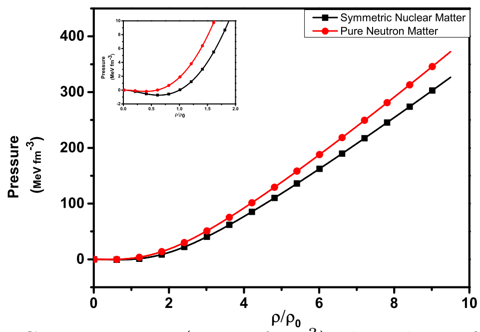

FIG. 2: Pressure ($MeV\ fm^{-3}$) plotted as a function of normalized baryon density.

Results

The nuclear matter saturation properties are: binding energy per nucleon $B/A - m = -16.3\ MeV$, nucleon effective mass $Y = m^{\star}/m = (0.83)$, incompressibility '$K = 240$ MeV', symmetry energy coefficient '$J = 30$MeV' at $\rho_0 = 0.16 fm^{-3}$.The nucleon, the vector meson and the isovector vector meson masses are taken to be 939 MeV, 783 MeV and 770 MeV respectively. The parameters of the model are $c_\sigma = (g_\sigma/m_\sigma)^2 = 7.37 fm^2$, $c_\omega = (g_\omega/m_\omega)^2 = 2.44 fm^2$ and $c_\rho = (g_\rho/m_\rho)^2 = 4.05 fm^2$, the coupling strengths for the scalar, vector and iso-vector meson respectively. The higher order couplings for the scalar field are $b/m^2 = -4.773 fm^2$ and $c/m^4 = 0.2 fm^4$ and $\xi = 9.8 fm^4$ for the vector field. The corresponding mass of the scalar meson is 540 MeV.

Conclusion

The inclusion of the term not only reduces the nucleon effective mass, but also has lowered the nuclear incompressibility to a more accepted value of 240 MeV. Moreover with regard to the symmetry energy coefficient and the slope parameter L we could obtain a reasonable value of 80 MeV which is 10% lower than the one obtained with the previous model.

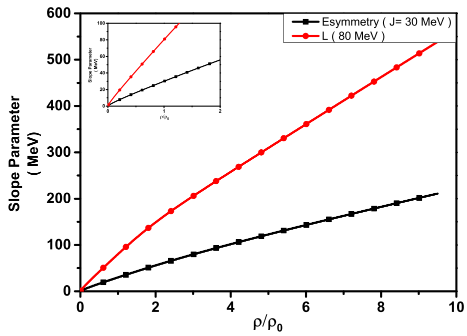

FIG. 3: Symmetry energy J and the slope parameter L plotted as a function of normalized baryon density.

Acknowledgments

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