Modified chiral potential and neutron stars

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Introduction

Chiral Symmetry is a global symmetry of strong interactions. The axial vector current is conserved under this symmetry. A Chiral Lagrangian model to illustrate Chiral Symmetry and partial conservation of axial vector current was first introduced by Gell-Mannn & Levy [1]. Subsequently the model was modified and applied to study of dense matter [2]. However, the main drawback of all those models was the unrealistic high nuclear incompressibility (K). Later on with inclusion of higher order terms of scalar meson field [3, 4] was introduced to ensure a reasonable value of K at saturation density, however resulting in a soft equation of state (EoS) at high densities. On similar grounds, we define a new `"Mexican-hat"` potential by introducing a parameter $'a'$. The model parameters are derived by satisfying the standard state nuclear matter saturation properties. In our preliminary analysis we find that we are able to not only reduce the matter incompressibility, but also the nucleon effective mass to desirable limits even without higher order in the scalar fields.

The Model

The interaction of the scalar and the pseudoscalar mesons with the vector boson generates a dynamical mass for the vector bosons through spontaneous breaking of the chiral symmetry with scalar field attaining the vacuum expectation value σ_0. Then the mass of the nucleon (m), the scalar meson (m_σ) and the vector meson mass (m_ω), are related to σ_0 through

$$m = g_\sigma \sigma_0, \quad m_\sigma = \sqrt{2\lambda}\sigma_0, \quad m_\omega = g_\omega \sigma_0 \ . \quad (1)$$

The modified Lagrangian of the present model is given by

$$\begin{aligned}
\mathcal{L} &= \bar{\psi}_B \Big[\Big(i\gamma_\mu \partial^\mu - g_\omega \gamma_\mu \omega^\mu - \frac{1}{2} g_\rho \vec{\rho_\mu}.\vec{\tau}\gamma^\mu \Big) \\
&- g_\sigma (\sigma + i\gamma_5 \vec{\tau}.\vec{\pi}) \Big] \psi_B + \frac{1}{2} \left(\partial_\mu \vec{\pi}.\partial^\mu \vec{\pi} + \partial_\mu \sigma \partial^\mu \sigma \right) \\
&- \boldsymbol{\frac{\lambda}{4} \left(\sigma^2 - \sigma_0^2 - a^2 \right)^2 - \frac{\lambda a^2}{2} \left(\sigma^2 - \sigma_0^2 - a^2 \right)} \\
&- \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} g_\omega^2 x^2 \left(\omega_\mu \omega^\mu \right) - \frac{1}{4} \vec{R_{\mu\nu}}.\vec{R^{\mu\nu}} \\
&+ \frac{1}{2} m_\rho^2 \left(\vec{\rho_\mu}.\vec{\rho^\mu} \right) \qquad (2)
\end{aligned}$$

The energy density (ϵ) and pressure (p) of symmetric nuclear matter (spin degeneracy, $\gamma = 4$) for a given baryon density (in terms of $Y = m^*/m$) in this model is obtained from the stress-energy tensor, which is given as

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

Results

The model parameters are obtained at nuclear matter saturation properties, which are: binding energy per nucleon $B/A - m = -16.3\ MeV$, nucleon effective mass $Y = m^*/m = 0.82$, incompressibility $K = 237\ MeV$ and the symmetry energy coefficient $J = 32\ MeV$ 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.

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TABLE I:

c_σ (fm^2)	c_ω (fm^2)	c_ρ (fm^2)	a (MeV)	m_σ (MeV)
4.84	2.32	4.52	38.50	650

The parameters of the model are given in Table [1]. As we can see that with minimum number of parameters in the model, we are able to bring down the nuclear incompressibility and effective mass as compared to the previous models. The EoS is compared with the Heavy Ion Collision(HIC) data [5] for both symmetric nuclear matter (SNM) and pure neutron matter (PNM) case as shown in Fig.[1]. We find that the EoS is stiffer now as compared with previous model predictions.

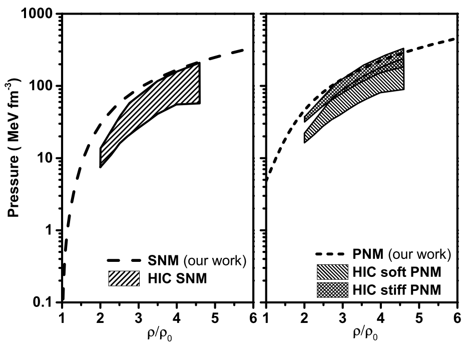

FIG. 1: Pressure as a function of scaled baryon density for SNM and PNM in this model.

Subsequently we apply the model to study neutron star structure and properties. We obtain neutron star maximum mass and radius to be 2.24 $M_\odot$ and 12.56 km respectively for $n-p-e$ beta-equilibrium matter. The radius $R_{1.4}$ solar mass neutron star is obtained to be 13.71 km.

The symmetry energy slope parameter L is 88 MeV and coefficient $J = 32$ MeV at nuclear saturation density is shown in fig 3.

Conclusions

With minimum parameterization, the modified model predicts reasonable incompressibility ($K = 237$ MeV) and symmetry energy coefficients, which is very motivating. In future work, we intend to investigate further the model and its applications.

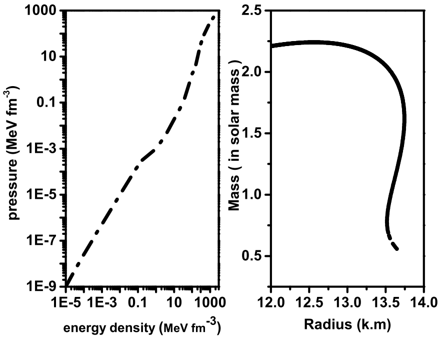

FIG. 2: (Left) EoS of $\beta-$ equilibrated npe matter and (Right) mass-radius relation for neutron star.

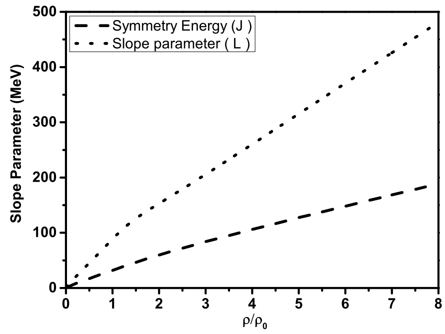

FIG. 3: Symmetry energy and its slope parameter versus baryon density.

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