Cross-couplings matters to matter at high densities

Naresh Kumar Patra[1], Tuhin Malik[1], T. K. Jha[1],* and B. K. Agrawal[2]
[1]*Department of Physics, BITS Pilani K K Birla Goa Campus, Goa - 403726, INDIA and*
[2]*Saha Institute of Nuclear Physics, Kolkata - 700064, INDIA*

Introduction

Understanding the behavior of nuclear symmetry energy both at low and high densities is fundamental to better understand both the finite nuclei and nuclear matter aspects such as Neutron Stars (NS) and supernovae dynamics. It also helps in understanding the aspects of the strong forces at high densities. Theoretically, one needs to modify the interactions so as to match the experimental data wherever available. Within the mean field ansatz, we analyze interactions based on chiral symmetry in which the isoscalar-vector meson mass is dynamically generated via Spontaneous Symmetry Breaking (SSB) by coupling the isoscalar-vector mesons with the scalar mesons [1, 2]. The non-linear terms in the chiral Lagrangian can provide the three-body forces which might have important roles to play at high densities. The effective chiral model has been used to study nuclear matter aspects such as matter at low density and finite temperature, NS structure and composition [3] and nuclear matter saturation properties.

In the present work, we employ and extend this model by including the cross-couplings of σ and ω mesons with the ρ meson. We would like to see whether these terms in the interaction help in fixing the values of symmetry energy and its slope parameter at the saturation density. We study the effects of the cross-couplings on the Equation of State (EoS) for Asymmetric Nuclear Matter (ANM) and the mass and the radius of NS are evaluated.

*Electronic address: `tkjha@goa.bits-pilani.ac.in`

Model & Parameters

The complete Lagrangian density for the effective chiral model which includes the various cross-coupling terms is given by,

$$\mathcal{L} = \mathcal{L}_{\prime} + \mathcal{L}_{\times}, \tag{1}$$

where,

$$\begin{aligned}
\mathcal{L}_{\prime} &= \bar{\psi}_B \Big[\left(i\gamma_\mu \partial^\mu - g_\omega \gamma_\mu \omega^\mu - \frac{1}{2} g_\rho \vec{\rho_\mu}.\vec{\tau}\gamma^\mu \right) \\
&- g_\sigma (\sigma + i\gamma_5 \vec{\tau}.\vec{\pi}) \Big] \psi_B + \frac{1}{2} \left(\partial_\mu \vec{\pi}.\partial^\mu \vec{\pi} + \partial_\mu \sigma \partial^\mu \sigma \right) \\
&- \frac{\lambda}{4} \left(x^2 - x_0^2 \right)^2 - \frac{\lambda b}{6m^2} (x^2 - x_0^2)^3 \\
&- \frac{\lambda c}{8m^4} (x^2 - x_0^2)^4 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} g_\omega^2 x^2 \left(\omega_\mu \omega^\mu \right) \\
&- \frac{1}{4} \vec{R_{\mu\nu}}.\vec{R^{\mu\nu}} + \frac{1}{2} {m'_\rho}^2 \vec{\rho_\mu}.\vec{\rho^\mu},
\end{aligned} \tag{2}$$

and

$$\mathcal{L}_{\times} = \eta_1 \left(\frac{1}{2} g_\rho^2 x^2 \vec{\rho_\mu}.\vec{\rho^\mu} \right) + \eta_2 \left(\frac{1}{2} g_\rho^2 \vec{\rho_\mu}.\vec{\rho^\mu} \omega_\mu \omega^\mu \right) \tag{3}$$

Here, ψ_B is the nucleon isospin doublet interacting with different mesons σ, ω and ρ, with the respective coupling strengths g_i, with $i = \sigma, \omega$ and ρ. The b and c are the strength for self couplings of scalar fields. γ^μ are the Dirac matrices and τ are the Pauli matrices.

$\mathcal{L}_\times$ (Eq. (3)) is the new additional piece we add to the original Lagrangian given in [3].

Results

For symmetry energy constraints, we consider the data from three important sources: simulations of low energy Heavy Ion Collisions (HIC) in ^{112}Sn and ^{124}Sn; nuclear structure studies by excitation energies to Isobaric Analog States (IAS) and ASY-EOS experiment at GSI. The density dependences of the symmetry energy for NCC, SR, WR and selected

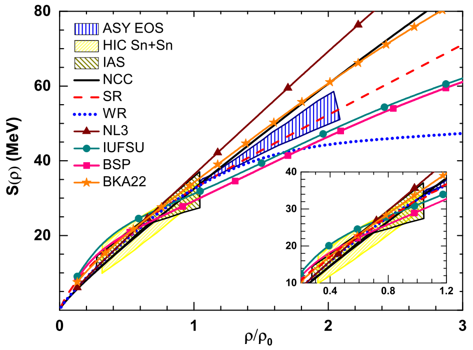

FIG. 1: (Color Online) Symmetry energy as a function of scaled density (ρ/ρ_0) is plotted for the NCC, SR and WR in the present work and are compared to other models. The inset shows the blown up behavior of symmetry energy at low densities.

RMF models are displayed in Fig. 1. We find that without any cross-couplings (NCC), the behavior of symmetry energy as a function of density is not very much compatible with those obtained by analyzing diverse experimental data. Remarkably the SR model satisfies all the above mentioned constraints. None of the considered RMF models satisfy all the symmetry energy constraints.

The maximum mass of the NS is sensitive neither to the methods used to estimate the crust effects nor to the choice of transition density. The radius of NS is sensitive to transition density. The mass radius relationship for the NS for all of our three models obtained using respective values of the transition densities are plotted in Fig. 2. It is found that the value of $R_{1.4}$ is decreased by ~ 0.5 km in SR model compared to NCC model. The $R_{1.4}$ of SR is consistent with 11.9 ± 1.22 km (90% confidence) obtained by constraining symmetry energy at saturation density. The NS maximum mass $M_{max} = 2.79, 1.94, 2.02, 2.04\ M_\odot$ and the radius $R_{1.4} = 14.66, 12.49, 12.64, 13.28$ km for the selected RMF models NL3, IUFSU, BSP and BKA22 respectively. The effect of cross-couplings on the RMF models seems to have weak effect than the cross-coupling as in the case of effective chiral model.

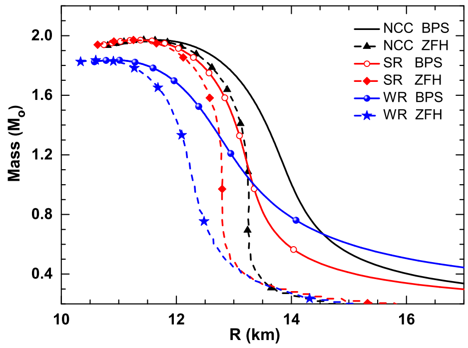

FIG. 2: (Color Online) The mass-radius relationships for the NCC, SR and WR models are displayed. The effects of the crustal EoSs are incorporated by using explicitly the BPS and polytropic EoSs (solid lines) at low densities and alternatively using the ZFH method (dashed lines).

Conclusions

With the $\sigma-\rho$ cross-coupling (SR), the overall behavior of the density dependence of the symmetry energy agree well with IAS, HIC Sn+Sn and ASY-EOS data. The value of the symmetry energy slope and the curvature parameters are in accordance with those deduced from the diverse set of experimental data for the finite nuclei. The SR model satisfies all the discussed constraints which suggest that the inclusion of $\sigma - \rho$ cross-coupling in the effective chiral model is indispensable.

References

[1] J. Boguta, Phys. Lett. **B128**, 19 (1983).

[2] P. K. Sahu, R. Basu, and B. Datta, Astrophys. J. **416**, 267 (1993).

[3] T. K. Jha, P. K. Raina, P. K. Panda, and S. K. Patra, Phys. Rev. **C74**, 055803 (2006), [Erratum: Phys. Rev.C75,029903(2007)].

[4] X. Roca-Maza, M. Brenna, B. K. Agrawal, P. F. Bortignon, G. Col, L.-G. Cao, N. Paar, and D. Vretenar, Phys. Rev. **C87**, 034301 (2013).