Effects of mesonic cross-coupling on symmetry energy : effective chiral model

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Introduction

Over the last decade or so there has been an extensive work and debate dedicated to understanding the behavior of nuclear symmetry energy theoretically as well as experimentally, both at low and high densities. This knowledge is helpful in understanding both finite nuclei and nuclear matter aspects such as neutron stars (NS) and supernovae dynamics, related to neutron-rich domain. Currently available data on nuclear masses and giant dipole polarizability have constrained the values of symmetry energy and its slope parameter to $J \sim 32$ MeV and $L \sim 50 - 80$ MeV [1], respectively, at the nuclear saturation density ($\rho \sim 0.16$ fm^{-3}).

In this contribution, we employ the effective chiral model (ECM) in which chiral symmetry breaks spontaneously. We have extended the ECM by including the contributions from $\sigma - \rho$ and $\omega - \rho$ mesonic cross-couplings. In the absence of these cross-couplings the values of nuclear symmetry energy and its slope parameters are little to large. The effects of the mesonic cross-couplings on the properties of the NS are also studied.

The effective chiral model

The Lagrangian density for the effective chiral model without any $\sigma - \rho$ and $\omega - \rho$ mesonic cross-couplings is given in Ref [2]. The $\mathcal{L}_\times$ (Eq. (1)) is the new additional piece we add to the original Lagrangian.

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

The energy density equation for a given baryon density (in terms of $Y = m^*/m$ and couplings parameters) in this modified model is given by,

$$\begin{aligned} \epsilon &= E(ke) + \frac{m^2}{8C_\sigma}(1-Y^2)^2 - \frac{b}{12C_\sigma C_\omega}(1-Y^2)^3 \\ &+ \frac{c}{16m^2 C_\sigma C_\omega^2}(1-Y^2)^4 + \frac{1}{2}m_\omega^2\omega_0^2 Y^2 + \frac{1}{2}m_\rho^2\Big[1 - \\ &\eta_1(1-Y^2)(C_\rho/C_\omega) + 3\eta_2 C_\rho \omega_0^2\Big](\rho_3^0)^2, \quad (2)\end{aligned}$$

where, $E(ke) = \frac{1}{\pi^2}\sum_{k_n,k_p}\int_0^{k_F} k^2\sqrt{k^2+m^{*2}}dk$. The values of coupling parameters C_σ, C_ω, b and c are adjusted to reproduced the properties of symmetric nuclear matter (SNM) at saturation density as listed in Table I. The coupling parameters

TABLE I: List of the model parameters determined from the properties of SNM such as, energy per nucleon $E_0 = -16$ MeV, nuclear incompressibility $K = 247$ MeV and the nucleon effective mass $Y = m*/m = 0.864$ at the saturation density $\rho_0 = 0.153$ fm^{-3}. The scalar and vector meson coupling parameters are $C_\sigma = g_\sigma^2/m_\sigma^2$ and $C_\omega = g_\omega^2/m_\omega^2$ respectively. $B = b/m^2$ and $C = c/m^4$ are the parameters for the higher order self-couplings of the scalar field with m being the nucleon mass. The nucleon, ω meson and σ meson masses are 939 MeV, 783 MeV and 469 MeV respectively.

C_σ (fm^2)	C_ω (fm^2)	B (fm^2)	C (fm^4)
7.057	1.757	-5.796	0.001

C_ρ, η_1 and η_2 are adjusted to obtained desired values of symmetry energy and its slope parameters. We consider three different variants of the ECM: NCC (no cross-coupling, $\eta_1 = \eta_2 = 0$), SR ($\sigma - \rho$ cross-coupling, $\eta_2 = 0$) and WR ($\omega - \rho$ cross-coupling, $\eta_1 = 0$). In Table II we list the values of coupling constants (C_ρ, η_1 and η_2) and the resulting nuclear matter properties: J_0, L, K_{sym}, Q_{sym} and K_τ at the saturation density ρ_0 and J_1 - the symmetry energy at $\rho_1 = 0.1$ fm^{-3}[3]. In case of SR and WR the values of J_0 and L are compatible with $J_0 = 31.6 \pm 2.66$ MeV and $L = 58.9 \pm 16$ MeV obtained by analyzing various terrestrial experimental informations and astrophysical observations [4]. The value of L obtained with NCC model is a little too large. The value of J_1 also shows a significant deviation from 23.6±0.3 MeV

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TABLE II: The values of the coupling constants C_ρ, η_1 and η_2 are determined from various symmetry energy elements. The mass of the ρ meson is 770 MeV. The values of C_ρ are in units of fm^2, η_1 and η_2 are dimensionless. All the symmetry energy elements are in units of MeV.

		NCC	SR	WR
Parameters	C_ρ	5.14	12.28	6.08
	η_1	0	-0.79	0
	η_2	0	0	6.49
Nuclear Matter	J_0	32.5	32.5	32.5
	J_1	22.30	24.49	23.68
	L	87	65	65
	K_{sym}	-20.09	-59.16	-204.78
	Q_{sym}	58.73	356.11	-88.04
	K_τ	-434	-368	-513

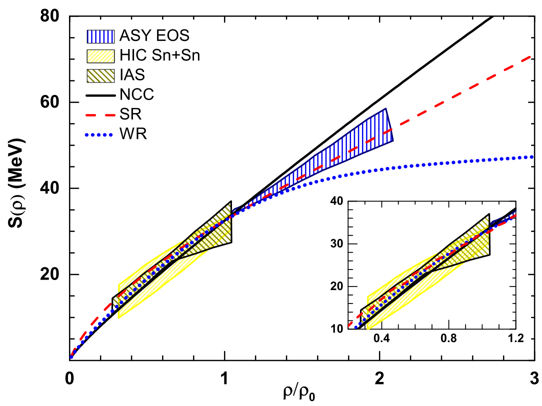

FIG. 1: (Color Online) Symmetry energy as a function of scaled density (ρ/ρ_0).

[5] obtained by analyzing the experimental data on isovector giant resonances, whereas, J_1 is in good agreement in case of SR and WR models.

Results and Discussions

The density dependences of the symmetry energy for NCC, SR and WR models are displayed in Fig. 1. For comparison we have depicted the data from 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 in the figure (see Ref. [3] and therein). It is evident that in the absence of 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 empirical data. Remarkably the SR model

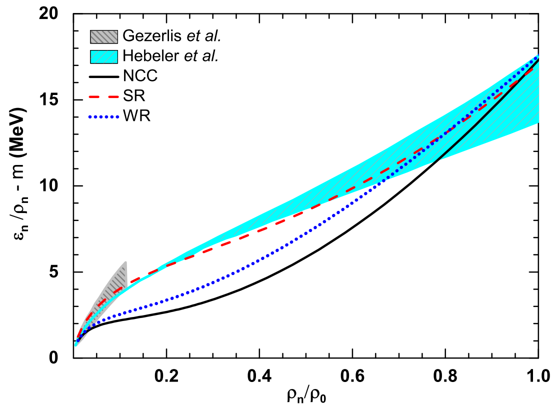

FIG. 2: (Color Online) Energy per neutron as a function of scaled neutron density (ρ_n/ρ_0).

satisfies all the above mentioned empirical data. In Fig. 2 we plot low density EoS for PNM for all of our three models (NCC, SR and WR). The low density behavior of energy per neutron for SR model is in good agreement with the results obtained by microscopic calculations as shown by the shaded region (see Ref. [3] and therein). The PNM EoS for NCC and WR models do not have much overlap with the shaded region. We find that by including $\sigma - \rho$ coupling (SR) NS maximum mass is 1.97 $M_\odot$ and radius at canonical mass, $R_{1.4}$ is 12.72 km, which is smaller $\sim$ 0.5 km compare to the NCC model which does not include any cross-coupling term. The WR model does not satisfy the maximum mass constraint of $2.01 \pm 0.04 M_\odot$.

Conclusions

The effective chiral model is extended by introducing the contributions from the cross-couplings between isovector and isoscalar mesons. These cross-couplings are found to be instrumental in improving the density content of the nuclear symmetry energy.

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