Effects of isovector cross-couplings on the properties of neutron stars

N. Alam[1],* A. Sulaksono[2], and B. K. Agrawal[1]
[1] *Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700064, India*
[2] *Departemen Fisika, FMIPA, Universitas Indonesia, Depok, 16424, Indonesia.*

The bulk properties of neutron stars depend crucially on the equation of state(EoS) of β-equilibrated dense baryonic matter. The matter inside the neutron star is highly asymmetric, thus, the EoS depends strongly on the density dependence of symmetry energy $S(\rho)$.The value of $S(\rho)$ is reasonably constrained only around saturation density $\rho_0(\sim 0.16\ \mathrm{fm}^{-3})$ by the bulk properties of finite nuclei. The $S(\rho)$ governs the neutron star(NS) properties such as radii, thickness of crust, rate of cooling etc [1]. In this work we study the effects on the properties of neutron stars arising due to the isovector cross-coupling terms which determine the behaviour of $S(\rho)$ in the extended relativistic mean field (ERMF) model.

The Lagrangian for the ERMF model can be written as [2, 3],

$$\mathcal{L} = \mathcal{L}_B^{free} + \mathcal{L}_{meson}^{free} + \mathcal{L}_{int}^{lin} + \mathcal{L}_{int}^{non\text{-}lin},$$

where, the first two terms denotes standard free Lagrangian for baryons and mesons. The linear and non-linear interaction part can be written as,

$$\mathcal{L}_{int}^{lin} = \overline{\Psi}_B[g_\sigma\sigma + g_\delta\delta\tau - g_\omega\gamma^\mu\omega_\mu - \frac{1}{2}g_\rho\gamma^\mu\tau.\rho_\mu]\Psi_B, \quad (1)$$

$$\mathcal{L}_{int}^{non\text{-}lin} = -\frac{\kappa_3}{6M}g_\sigma m_\sigma^2\sigma^3 - \frac{\kappa_4}{24M^2}g_\sigma^2 m_\sigma^2\sigma^4 + \frac{1}{24}\zeta_0 g_\omega^2(\omega_\mu\omega^\mu)^2 + \frac{\eta_1}{2M}g_\sigma m_\omega^2\sigma\omega_\mu\omega^\mu + \frac{\eta_2}{4M^2}g_\sigma^2 m_\omega^2\sigma^2\omega_\mu\omega^\mu + \frac{\eta_\rho}{2M}g_\sigma m_\rho^2\sigma\rho_\mu\rho^\mu + \frac{\eta_{1\rho}}{4M^2}g_\sigma^2 m_\rho^2\sigma^2\rho_\mu\rho^\mu + \frac{\eta_{2\rho}}{4M^2}g_\omega^2 m_\rho^2\omega_\mu\omega^\mu\rho_\mu\rho^\mu. \quad (2)$$

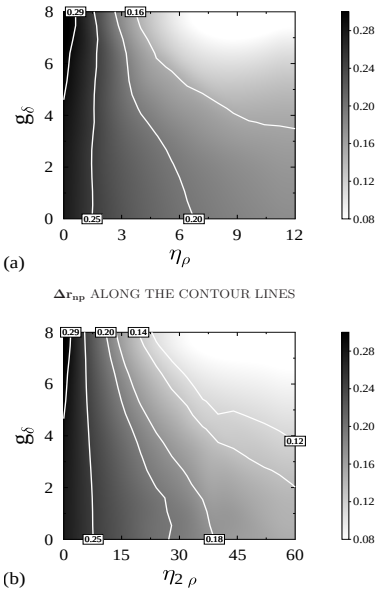

FIG. 1: Contours in the $g_\delta - \eta_\rho$(upper panel) and $g_\delta - \eta_{2\rho}$(lower panel) planes corresponding to the F_ρ and $F_{2\rho}$ families, respectively. The values of $\Delta r_{\rm np}$ are fixed along the contour lines.

The NS properties are calculated for two different families of models, namely, F_ρ and $F_{2\rho}$. $F_\rho(F_{2\rho})$ family includes σ-$\rho(\omega$-$\rho)$ cross-coupling whose strength is determined by η_ρ $(\eta_{2\rho})$. Both the families include the lowest order contributions from the δ mesons. In addition, other interaction terms usually present in RMF models are also considered. The σ-ρ and ω-ρ cross-coupling terms enables one to vary the density dependence of the symmetry energy coefficient and the neutron skin thickness in heavy nuclei over a wide range without affecting the other properties of finite nuclei. In Fig.1 the relationships of the parameters g_δ and $\eta_\rho(\eta_{2\rho})$ with the neutron skin thickness in the ^{208}Pb nucleus for the $F_\rho(F_2\rho)$ are displayed in terms of the contour plot. For

*Electronic address: naosad.alam@saha.ac.in

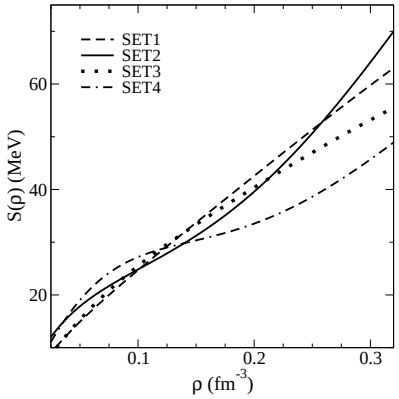

FIG. 2: The density dependence of symmetry energy $S(\rho)$ for some representative cases of F_ρ and $F_{2\rho}$ families of the models.

a given value of g_δ and η_ρ or $\eta_{2\rho}$, the g_ρ is adjusted to reproduce the binding energy of ^{208}Pb nucleus. The values of $\Delta r_{\rm np}$ decreases with increasing g_δ, η_ρ or $\eta_{2\rho}$.

We present our results only for the four representative sets of parameters. The SET1 and SET2 belong to the F_ρ family, while, SET3 and SET4 are for the $F_{2\rho}$ family. The SET1 and SET3 do not include the contributions from the δ mesons ($g_\delta = 0$). The SET2 and SET4 correspond to the higher value of the δ-nucleon coupling strength ($g_\delta = 8$). SET1-SET4 are so obtained that the comparison of the NS properties resulting from them give us a crude estimate about the effects of δ meson as well as the σ-ρ and ω-ρ cross-couplings.

In Fig.2 we display the variations of symmetry energy as a function of density for different parameterizations. The high density behaviour for the symmetry energy is stiffer for the F_ρ family as can be easily verified by comparing the results for the SET1 and SET2 with those for the SET3 and SET4, respectively. Further, by comparing the results for the SET1 with SET2 or those for SET3 with SET4, it can be concluded that the inclusion of the δ mesons softens the symmetry energy at low densities while makes it stiffer at higher densities.

In Table I the results for the various properties of the neutron stars obtained for these representative cases corresponding to the F_ρ and $F_{2\rho}$ families are summarized. The values of neutron-skin thickness for the ^{208}Pb nucleus are also listed. Inclusion of the δ mesons decrease the values of $\Delta r_{\rm np}$. The values of core-crust transition density ρ_t, corresponding pressure P_t, threshold density ρ_{DU} and mass M_{DU} for cooling through direct Urca process are higher for the $F_{2\rho}$ family. But the trend is opposite for $\lambda_{1.4}$, the tidal polarizability parameter of neutron star with mass $1.4M_\odot$. The value of $M_{\rm max}$ increasing but $R_{1.4}$ slightly decreasing with the inclusion of δ mesons for both the families. It may be easily seen from Table 1 that there are large variations in the properties of neutron star across the families at fixed values of $\Delta r_{\rm np}$ in the ^{208}Pb nucleus. We may thus say that the simultaneous inclusion of the σ-ρ and ω-ρ cross-couplings in the extended RMF model would enhance its flexibility to accommodate the variations in the properties of the neutron stars at a given neutron-skin thickness.

TABLE I: Neutron star properties and the neutron-skin thickness in the ^{208}Pb nucleus obtained for SET1 -SET4 parameters.

	F_ρ		$F_{2\rho}$	
Properties	SET1	SET2	SET3	SET4
$\Delta r_{\rm np}$ (fm)	0.22	0.15	0.22	0.15
ρ_{DU} (fm^{-3})	0.297	0.282	0.401	0.505
ρ_t(fm^{-3})	0.058	0.069	0.073	0.107
P_t (MeV fm^{-3})	0.222	0.107	0.474	0.509
$R_{1.4}$(km)	13.08	12.96	13.00	12.37
$M_{\rm max}(M_\odot)$	1.95	2.02	1.91	1.97
$M_{DU}(M_\odot)$	1.01	1.09	1.33	1.69
$\lambda_{1.4}$ (10^{36} cm^{2}g s^2)	3.41	4.33	2.87	2.88

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