Symmetry energy effects on the Equation of State of dense matter

B. K. Sharma[1]* and T. K. Jha[2]

[1]*Department of Nuclear and Atomic Physics, Tata Institute of Fundamental Research, Mumbai - 400005, INDIA and*
[2]*Physics Group, Birla Institute of Technology and Science, Pilani - K. K. Birla Goa Campus, Goa - 403726, INDIA*

Introduction

Nuclear symmetry energy and its density dependence plays an important role in finite nuclei as well as neutron stars. The development of radioactive beam facilities has enabled us to explore the neutron-rich matter where, symmetry energy effects seems to be well pronounced. Further, the composition, dynamics and stability of neutron star are strongly influenced by the density dependence of the symmetry energy. On the experimental side, the Heavy-ion collisions can reveal the density dependence of symmetry energy of dense matter. In this work we investigate the effects of density dependant symmetry energy on the EOS of neutron star in a field theoretical model within the framework of the Relativistic mean-field theory.

Theoretically one constructs an EOS where the symmetry energy rises monotonously with the density or the symmetry energy increase initially up to ρ_0 or slightly beyond and then decreases with the density. The exact form of density dependence of symmetry energy also depends on the nature and form of the interactions.

In the present work, we explore the symmetry energy effects on neutron star matter by using standard relativistic mean field (RMF) model with nonlinear isoscalar-isovector coupling Λ_v. This additional new coupling in RMF model, provides an efficient way to regulate the density dependence of nuclear symmetry energy.

*Electronic address: bksharma@tifr.res.in

Formalism

The Lagrangian density that we use in the present context is given in [1]. The symmetry energy for this Lagrangian is given by

$$E_{\rm sym}(\rho) = \frac{k_F^2}{6E_F^*} + \frac{g_\rho^2}{12\pi^2}\frac{k_F^3}{m_\rho^{*2}}, \qquad (1)$$

where $E_F^* = \sqrt{k_F^2 + m^{*2}}$ and the nucleon Fermi momentum and effective mass are k_F and $m^* = m - g_s\phi_0$. The effective rho-meson mass is $m_\rho^{*2} = m_\rho^2 + 2g_\rho^2(\Lambda_v g_v^2 V_0^2)$.

We use the recently proposed NL3* parameter set [2] with addition of isoscalar-isovector coupling Λ_v. All the combinations of Λ_v and g_ρ is adjusted to $E_{\rm sym}(\overline{\rho}) = 26.35$ MeV at an average density $\overline{\rho}$ corresponding to $k_F = 1.15 fm^{-1}$ where the binding energy of ^{208}Pb is reproduced. Since it has been noted that the skin thickness of neutron-rich heavy nucleus, for example, ^{208}Pb, are linearly correlated with symmetry pressure at a density slightly below the ρ_0. Since the same pressure supports a neutron star at supranormal densities against gravitational collapse, suggests an underlying correlation between neutron skin of heavy nuclei and neutron star radii.

Results

Figure 1 shows the density dependence of the nuclear symmetry energy $E_{\rm sym}(\rho)$ at various isoscalar-isovector coupling Λ_v for the NL3* parameter set. The sets show the systematic trend that a stiffer symmetry energy at supranormal densities $\rho \gtrsim \rho_0$ leads to a softer energy dependence at sub-saturation densities. The $\Lambda_v = 0$ set exhibits almost linear density-dependent symmetry energy behavior which can be realized from Eq. (1) as

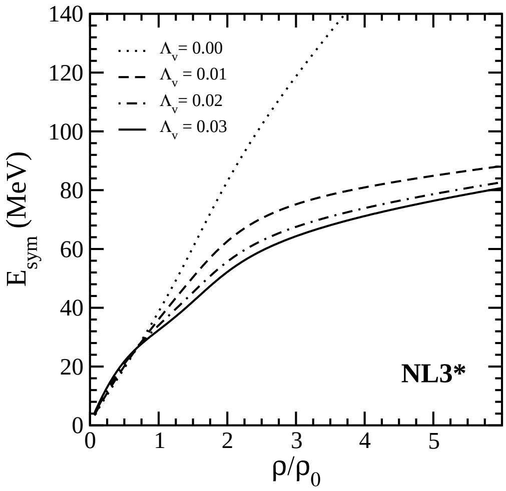

FIG. 1: Density dependence of symmetry energy for different couplings of Λ_v.

$E_{\rm sym}(\rho) \propto k_F^3 \propto \rho$ at high densities.

TABLE I: Results for the NL3* parameter set. The slope parameter L and $K_{\rm asy} \approx K_{\rm sym} - 6L$ are given.

Λ_v	g_ρ^2	L (MeV)	$K_{\rm asy}$ (MeV)
0.000	83.72	122.634	-630.244
0.010	96.06	88.838	-586.450
0.020	112.69	67.819	-461.039
0.030	136.26	54.290	-325.945

The slope and curvature parameters that determine the density dependence of $E_{\rm sym}$ at ρ_0 are $L = 3\rho_0 E_{\rm sym}(\rho)/\partial\rho|_{\rho_0}$ and $K_{\rm sym} = 9\rho_0^2 \partial^2 E_{\rm sym}(\rho)/\partial^2\rho|_{\rho_0}$, respectively. The incompressibility of asymmetric nuclear matter with an asymmetry $\delta = (\rho_n - \rho_p)/\rho$ can be expressed as $K_\delta = K_0 + K_{\rm asy}\delta^2$, where the density dependence of the symmetry energy is embedded in $K_{\rm asy} \approx K_{\rm sym} - 6L$. Estimates of $L = 88 \pm 25$ MeV and $K_{\rm asy} = -500 \pm 50$ MeV have been obtained from isospin diffusion data [3]. Whereas the isoscaling data [4] predict $L \approx 65$ MeV and $K_{\rm asy} \approx -453$ MeV, and from nucleon emission ratios $L \sim 55$ MeV has been extracted. From the L and $K_{\rm asy}$ values obtained for the NL3* in Table I it appears that all sets with $\Lambda_v \lesssim 0.03$ gives symmetry energy that are consistent with the constraint of $L = 88 \pm 25$ MeV and $K_{\rm asy} = -500 \pm 50$ MeV or -550 ± 100 MeV around the saturation density.

References

[1] B. G. Todd and J. Piekarewicz, Phys. Rev. **C67**, 044317 (2003).

[2] G. A. Lalazissis, S. Karatzikos, R. Fossion, D. Pena Arteaga, A. V. Afanasjev, P. Ring, Phys. Lett. **B671**, 36 (2009).

[3] B.-A. Li, L.-W. Chen and C.M. Ko, Phys. Rep. **464**, 113 (2008).

[4] D.V. Shetty, S.J. Yennello and G.A. Souliotis, Phys. Rev. **C76**, 024606 (2007).