Effect of symmetry energy slope parameter on nuclear matter and neutron star properties

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Introduction

The physics of neutron stars (NSs) have acquired huge attention over the years after the detection of gravitational waves from binary merger GW170817. Recent PREX-2 data yields the value of symmetry energy (E_{sym}) = 38.1 ± 4.7 and the symmetry energy slope (L_{sym}) = 106 ± 37 [1, 2]. L_{sym} also affects the structural properties of NSs but the exact value of L_{sym} is still uncertain. Considering the different constraints and the PREX data, the presently accepted range is L_{sym}={30.6, 86.8} [2].

In this work we study how L_{sym} affects the E_{sym} as well as the NS properties. For the purpose we consider the matter to be hadronic and the model is based on the framework of relativistic mean field theory (RMF). The main feature of this work is that we consider density dependent RMF parameterization (DDMEX) to model the NS matter (NSM).

Formalism

The Lagrangian for hadronic matter and leptonic matter (e^-,μ^-)is

$$\mathcal{L}_{RMF} = \bar{\psi}(g_\sigma\sigma - g_\omega\gamma_\mu\omega^\mu - \frac{1}{2}g_\rho\gamma_\mu\tau.\rho^\mu)\psi + \mathcal{L}_f + \mathcal{L}_{lep} \quad (1)$$

where ψ indicates the Dirac fields for the nucleons, m is the mass of the nucleons, $\mathcal{L}_f$ is the free part of the nucleons and mesons and $\mathcal{L}_{lep}$ is leptonic contribution.

The coupling constants are defined as

$$g_i = g_i(\rho_0)a_i\frac{1 + b_i(x + d_i)^2}{1 + c_i(x + d_i)^2} \quad (2)$$

$$g_\rho = g_\rho(\rho_0)exp(-a_\rho(x - 1)), x = \frac{\rho}{\rho_0} \quad (3)$$

where $i = \sigma$,ω and ρ_0 is saturation density. The DDMEX model parameters is given in [2]. We use mean field approximation. The energy density and pressure expressions are given in [2].

$$\delta = \frac{\rho_n - \rho_p}{\rho} \quad (4)$$

Here δ=0 gives symmetric nuclear matter(SNM) and δ=1 gives pure neutron matter. The energy difference between these two δs gives symmetry energy(E_{sym}). The symmetry energy slope parameter is defined as

$$L_{sym} = 3\rho_0\big(\frac{\partial E_{sym}}{\partial\rho}\big)_{\rho_0} \quad (5)$$

Results

TABLE I: Saturation properties of DDMEX model.

$\rho_0(fm^{-3})$	BE/A (MeV)	E_{sym} (MeV)	L_{sym}
0.152	-16.34	33.36	52.66

In table 1 we report the value of L_{sym} = 52.2 for the chosen parameterization with SNM. To study the effect of L_{sym}, we vary L_{sym} via a_ρ without changing any other saturation property. The fitted form of a_ρ is given by

$$a_\rho = a_1L_{sym} + a_2 \quad (6)$$

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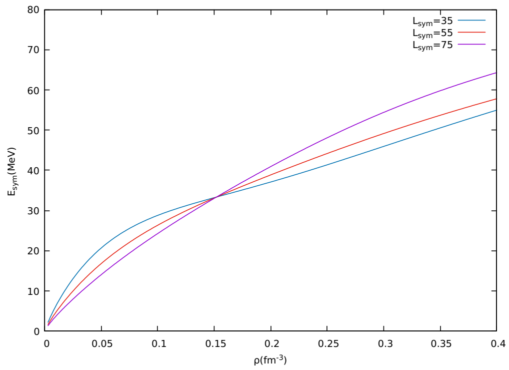

FIG. 1: Variation of symmetry energy with density for different L_{sym} for SNM.

a_1=−0.0126915 and a_2=1.28838.We take L_{sym}=35,55,75 and the corresponding a_ρ=0.8442,0.6145,0.1702.

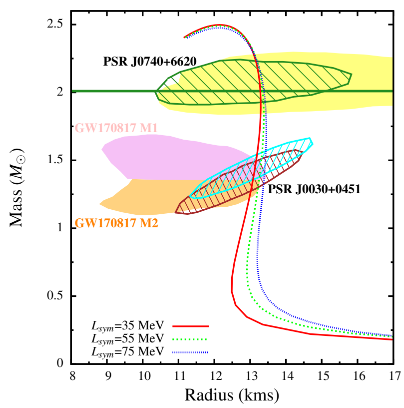

FIG. 2: Variation of mass w.r.t radius for different L_{sym}.

In fig[1] we plot the symmetry energy for SNM vs density for different L_{sym}. For this density dependent model we see that below the saturation density, lower the L_{sym}, the higher the g_ρ; but above ρ_0, the reverse trend is noticed. The lowering of g_ρ with increasing density implies that the coupling between nucleons and ρ meson become weaker as the density increases. We also found that for low density, higher the L_{sym} lower the E_{sym} but for higher density the scenario is opposite.

On the other hand, to see the effect of L_{sym} on equation of state (EoS) of NS, we solve mean field equations for the charge neutral β stable hadronic matter as NSM. Using these EoS obtained with different L_{sym}, we solved the Tolman-Oppenheimer-Volkoff (TOV) to obtain the mass and radius of the NSs. In fig[2] we plot mass-radius for different L_{sym}. At low density (below ρ_0), the observed effect of L_{sym} is also reflected in the mass-radius variation. From $M - R$ plot we find that for all the values of L_{sym}, the maximum gravitational mass do not differ much but satisfy the maximum mass constraint from PSRJ0740+6620 and its corresponding radius. For all the considered values of L_{sym}, the constraints from GW170817 and NICER data for PSRJ0030+0451 are also satisfied. It can be seen that the radius of intermediate and low mass NSs decrease with lower values of L_{sym}.

Summary and Conclusion

We applied RMF model with DDMEX parameterizations to describe nuclear matter as well as NS properties. We have investigated the effect of L_{sym} on E_{sym} and mass-radius of NSs by varying the value of L_{sym} consistent with the PREX-2 data via the parameter a_ρ. We found that below ρ_0, the higher the L_{sym}, lower the E_{sym}; while the opposite trend is noticed above ρ_0. This effect is reflected correspondingly in the mass-radius variation of β stable NSM as the radius of intermediate mass NSs, specially $R_{1.4}$ is well affected by the value of L_{sym}. Lower values of L_{sym} lowers the value of $R_{1.4}$, thereby satisfying the GW170817 data better without much effect on the maximum mass of the NS.

References

[1] X. Wu et al., Phys.Rev.C 104 (2021) 1, 015802.

[2] V. B. Thapa et al. Phys.Rev.C 105 (2022) 1, 015802.