Role of symmetry energy on the inner crust composition of neutron star

Vishal Parmar[1],* Manoj K Sharma[1], and S K Patra[2,3]
[1] *School of Physics and Materials Science,*
Thapar Institute of Engineering and Technology, Patiala-147004, India
[2] *Institute of Physics, Bhubaneswar 751005, India and*
[3] *Homi Bhaba National Institute, Training School Complex,*
Anushakti Nagar, Mumbai 400 085, India

Introduction

In the last few years, the investigation of the neutron star (NS) structure and associated dynamics has taken a central stage in astrophysical sciences and gravitational-wave astronomy. It provides us with the most advanced cosmic laboratory to test the nuclear theory against various neutron star phenomena and, in turn, helps to constrain the nuclear matter observables. The neutron star is broadly divided into atmosphere, crust (outer and inner), and core. Out of these, the neutron star's crust is the most crucial layer due to its complexity and importance in multiple neutron star properties such as the crustal moment of inertia, rotational frequency, quasi-periodic oscillations (QPOs) in soft gamma repeaters (SGRs) and cooling, etc [1, 2].

The inability to measure the mass of the nuclei in the free neutron gas environment [1] prompts us to use nuclear models to determine the inner crust structure of the neutron star. These models differ in their saturation properties, such as symmetry energy, incompressibility, etc. Among these, the symmetry energy is one of the most significant properties, which affects several NS observables [3]. Therefore, studying the implication of symmetry energy on inner crust structure becomes highly desirable. In this work, we investigate the role of symmetry energy on neutron star crust using the effective relativistic mean field (E-RMF) theory employing the compressible liquid drop model (CLDM).

Formalism

In the inner crust, we assume Wigner-Seitz (WS) cell which consists of a cluster surrounding ultrarelativistic electron gas and ambient neutron gas. The energy of this cluster can be written as [4]

$$E_{WS} = M_i(A,Z)+E_e+V_{WS}(\mathcal{E}_g+\rho_g M_n), \quad (1)$$

where $M_i(A,Z)$ is the mass of the cluster and M_n is the masses of nucleon. $\mathcal{E}_g$, and ρ_g are the energy density and density of the neutron gas respectively. We use the compressible liquid drop model (CLDM) to determine the energy of the cluster which reads [1, 4]

$$E_{cl} = E_{bulk}(\rho_0, I)A + E_{surf} + E_{curv} + E_{coul}, \quad (2)$$

where E_{surf}, E_{curv}, and E_{coul} are surface, curvature and Coulomb energy respectively. The E_{bulk} is taken from the effective relativistic mean field model (E-RMF). The equilibrium composition of inhomogeneous matter in the inner crust is obtained by minimizing the energy of WS cell per unit volume at a given baryon density ($\rho_b = \rho_n + \rho_p$), where ρ_n and ρ_p represent the neutron and proton density respectively.

Results and Discussions

To ascertain the role of symmetry energy (J), we consider 10 E-RMF parameters: FSUGarnet, IU-FSU, IUFSU*, G3, IOPB-I, SINPB, BKA24, FSU2, G1, and GL97 [1] with different symmetry energy. These parameter sets are consistent with various nuclear matter, and neutron star observables such as incompressibility, flow data, etc. [5]. Since the typical density of neutron star crust lies in the

---

*Electronic address: `physics.vishal01@gmail.com`

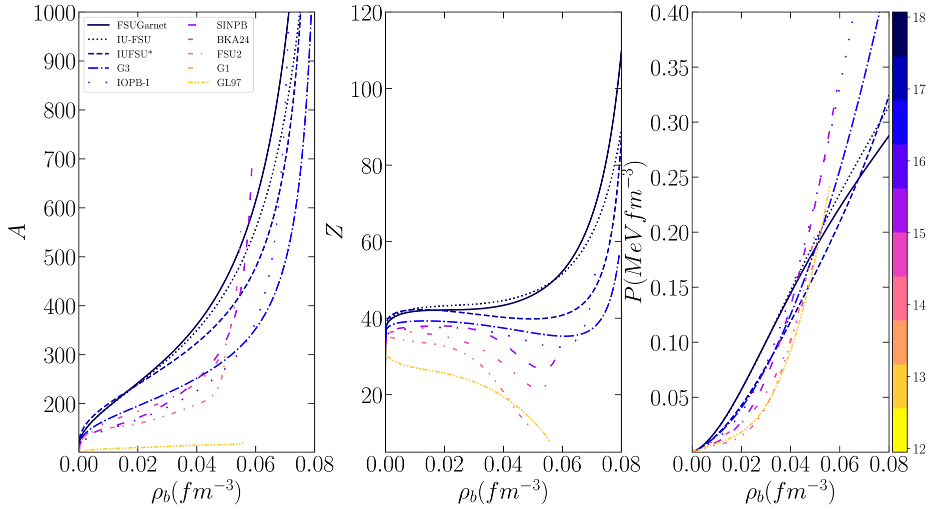

FIG. 1: (Color online) The distribution of atomic number (Z) , mass number (A) in the inner crust of neutron star and its equation of state as function of density. The color map represent the value of symmetry energy at 0.05 fm^{-3}.

sub-saturation density, we use the symmetry energy value at 0.05 fm^{-3} to take care of the the behavior of symmetry energy across the saturation density [1].

In Fig. 1, we show the equilibrium composition of the inner crust of neutron star using various E-RMF forces. The color map represents the symmetry energy value at (= 0.05 fm^{-3}). The number of nucleons (A) increase monotonically with density in the inner crust. A sharp increase is observed while approaching the crust-core transition indicating that the matter is transiting to the homogeneous phase. The E-RMF forces having larger symmetry energy at sub-saturation density estimate a larger value of (A).

Most of the inner crust is populated with charge number $Z \approx 40$, consistent with the various quantum calculations [2]. The E-RMF forces with lower symmetry energy predict decrement in the value of charge number when approaching the crust-core transition, while it keeps increasing with the symmetry energy. This behavior of the equilibrium composition inside the inner crust will have significant implications for calculating the frequency of QPOs, rotation frequency, and crust mass. Furthermore, a higher value of J estimates an almost linear behavior of EoS, while the lower symmetry energy results in exponential behavior. This means that the crust-core transition pressure and density depend on the symmetry energy behavior.

The above observations clearly show that symmetry energy significantly impacts the inner crust composition. Therefore, a stringent determination of nuclear symmetry energy is essential to constrain and better estimate the crustal properties of the neutron star.

References

[1] V. Parmar *et al.*, Phys. Rev. D **105** (2022) 043017, Phys. Rev. D **106** (2022) 023031.
[2] K. Oyamatsu *et al.*, Phys. Rev. C **75** (2007) 015801.
[3] W. G. Newton *et al.*, Astrophys. J. Suppl. Ser. **204** (2013) 9.
[4] T. Carreau *et al.*, A&A **640** (2020) A77.
[5] M. Dutra *et al.*, Phys. Rev. C **90** (2014) 055203.