Study of surface properties of neutron stars using coherent density fluctuation model

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Introduction

Neutron stars are densely packed remnants of massive stars, which have ended their life cycles in supernova explosions and serve as natural laboratories for investigating the physics of matter under extreme conditions. With masses approximately twice that of the Sun and diameters close to 20 kilometres, neutron stars exhibit densities that are about 5 to 10 times the nuclear saturation density [1]. By simulating these conditions through nuclear collisions on Earth, scientists can gain deeper insights into the fundamental properties of nuclear matter.

In conditions of exceedingly high densities, the equation of state (EoS) governs the behaviour of matter. This crucial concept in neutron star physics encapsulates the relationship between pressure, density, and temperature under these severe conditions. The EoS is instrumental in determining a broad spectrum of neutron star properties, including mass, radius, and internal composition [1]. The variety and intricacy of EoS models mirror our partial understanding of the strong force under such extreme conditions and highlight the necessity for theoretical investigations coupled with observational data to constrain these models. The challenge resides in developing EoS models that accurately reflects the extreme conditions within neutron stars while aligning with observational data. Only through a fusion of theoretical progress and observational studies can we aspire to unravel the mysteries of these enigmatic celestial objects. In Ref. [2], multiple Skyrme EOS have been identified that meet a set of criteria based on the macroscopic properties of nuclear matter near nuclear saturation density at zero temperature, as well as their density dependence, which is derived from the liquid-drop model, in experiments involving giant resonances and heavy-ion collisions.

Recently coherent density fluctuation model (CDFM) [3, 4] have triumphed in consistently studying finite and infinite nuclear matter [1, 3, 4, 5, 6]. In the present work, we utilize the CDFM formalism to study the surface properties, especially the symmetry energy of neutron stars, using of the widely used set of Skyrme force parameters (GSKI, GSKII, KDE0v1, and LNS), which are consistent with the constraints imposed in Ref. [2]. To note, the energy density functional of neutron star matter in momentum space is transformed into coordinate space using a local density approximation. These functionals are utilized to derive the surface properties of neutron stars within the coherent density fluctuation model, employing the weight function derived from the neutron star's density profile.

Theoretical Formalism

The structural properties of neutron stars (NS) are studied by solving the Tolman-Oppenheimer-Volkoff (TOV) equations as described in Ref. [1]:

$$\frac{dP}{dr} = -\frac{(\epsilon + P)(m + 4\pi r^3 P)}{r^2\left(1 - \frac{2m}{r}\right)}, \qquad (1)$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon \quad . \qquad (2)$$

The coupled TOV equations are solved with the boundary conditions: $(r = 0, P = P_c)$ and

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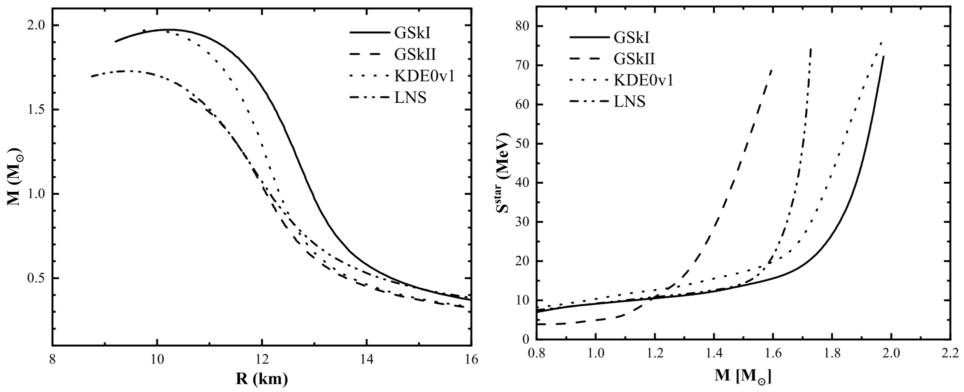

FIG. 1: The calculated (a) mass-radius (M-R) profile of neutron star and (b) symmetry energy (S^{star}) as a function of neutron star mass for some consistent Skyrme parameters satisfying all the constraints as imposed in Ref. [2].

($r = R, P = 0$). The maximum mass and radius of the neutron star are determined under the assumption that pressure becomes zero at the star's surface.

We parameterize equation of state using different Skyrme forces that meet all the constraints outlined in Ref. [2], which will be employed within the CDFM model. Within the CDFM, symmetry energy (S) is calculated as [3, 4]:

$$S^{star} = \int_0^\infty dx |\mathcal{F}(x)|^2 S^{NM}(x), \qquad (3)$$

where $|\mathcal{F}(x)|^2$ denotes the weight function, while $S^{NM}(x)$ represents the symmetry energy at local density [3, 4, 5].

Results and discussion

Figure 1 (a) illustrates the mass-radius profile of the neutron star. The figure indicates that the GSkI parameter set yields the maximum mass for the neutron star, while the GSkII parameter set results in the lowest mass. Additionally, using the CDFM formalism, we estimate the symmetry energy of the neutron star by providing its density and calculating the weight function. Figure 1 (b) illustrates the relationship between symmetry energy S^{star} and neutron star mass. The S^{star} of the neutron star at maximum mass exceeds the value of symmetric nuclear matter at saturation [1]. This observation is apparent across all four Skyrme parameters employed. Furthermore, the value of S^{star} is noted to be minimal for lower masses, while it rises at the maximum mass of the star. The structural dependence of the symmetry energy corresponds with the conclusions presented in Ref. [1]. A detailed examination of the surface properties of the neutron star is underway and will be communicated shortly.

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