Properties of Finite Nuclei and Neutron Star using Coherent Density Fluctuation Model

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1. Introduction

The relativistic mean-field (RMF) theory is the most essential and satisfactory phenomenological model to understand the statics and dynamics of finite nuclei and astrophysical objects. Modern study of infinite nuclear matter based on RMF model bestow us with new dimensions in understanding the nature and behavioral aspects of compact astrophysical objects [1]. Therefore, here we provide an approach to explore the nuclear and structural properties of nuclei and neutron star using coherent density fluctuation model (CDFM) with RMF equation of state being the main ingredient. We obtained a density-dependent analytical expression of binding energy per nucleon for different neutron-proton asymmetry of a dense matter with a polynomial fitting, which manifests the results of effective field theory motivated RMF model. This expression has the edge over the Br*ü*ckner energy density functional [2], since it resolves the Coster-Band problem. Further, nuclear properties like, incompressibility, symmetry energy, slope and curvature parameters, of the neutron star are calculated using the relativistic energy density functional within the framework of coherent density fluctuation model. The fascinating structural and compositional resemblance of finite nuclei and neutron stars allude us that the physics of compact objects can be explored by extrapolating the data of terrestrial experiments and theoretical formulization of dense matter systems. The equation of state (EoS) of strong interacting dense matter is the key component for the determination of general properties of neutron star like maximum mass, radius, tidal deformability. Therefore, to explore the properties of neutron star along with finite nuclei, we apply the RMF formalism to obtain the EoS for a dense matter system, where along with the neutrons and protons, electrons are also present to maintain the charge neutrality. We will denote this kind of infinite dense matter (consisting neutron, proton and electron) as neutron star matter.

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2. Formalism

The nuclear and structural properties of the neutron star, i.e. incompressibility (K^{star}), symmetry energy (S^{star}), slope parameter (L^{star}_{sym}) and curvature (K^{star}_{sym}), can be expressed in terms of weight function ($|F(x)|^2$) and the expression of the parameters evaluated from the energy density functional (eq. 6) of infinite star matter system, [3] as,

$$K^{star} = \int_0^\infty dx\, |F(x)|^2\ K^{NSM}(n(x)), \quad (1)$$

$$S^{star} = \int_0^\infty dx\, |F(x)|^2\, S^{NSM}(n(x)), \quad (2)$$

$$L^{star}_{sym} = \int_0^\infty dx\, |F(x)|^2\, L^{NSM}_{sym}(n(x)), \quad (3)$$

$$K^{star}_{sym} = \int_0^\infty dx\, |F(x)|^2\ K^{NSM}_{sym}(n(x)), \quad (4)$$

The $|F(x)|^2$ for a given density n (r) is expressed as

$$|F(x)|^2 = -\frac{1}{n_0(x)}\frac{dn(r)}{dr}\bigg|_{r=x}, \quad (5)$$

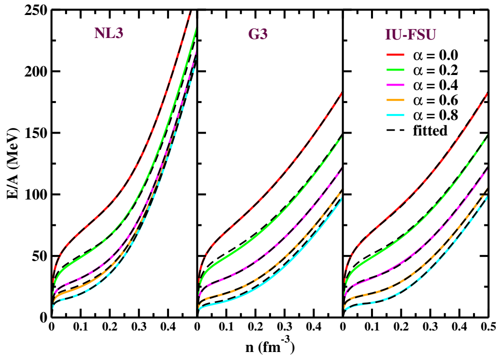

FIG. 1: The neutron star matter saturation curves as a function of baryon number density for different asymmetry $\alpha = \frac{n_n - n_p}{n_n + n_p}$ parameter. The solid curve represents the RMF numerical data and the dotted black curve stands for the fitted expression.

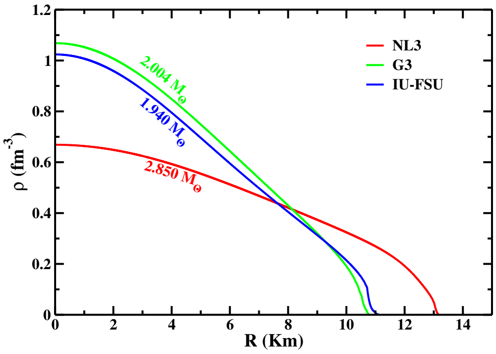

FIG. 2: The neutron star densities (ρ) for NL3 (red), G3 (green) and IU-FSU (blue) parameter sets as a function of radius of the maximum mass star (R). The mass number (A) of the maximum mass neutron star for NL3, G3 and IU-FSU are 3.35×10^{54}, 2.32×10^{54} and 2.23×10^{54} respectively.

3. Results and Discussion

The fitted binding energy function (Fig. 1) of RMF for neutron star matter is embedded in the following equation,

$$\mathcal{E} = C_k n^{2/3} + C_e n^{4/9} + \sum_{i=3}^{14} (b_i + a_i \alpha^2) n^{i/3}, \tag{6}$$

where C_k and and C_e are the kinetic energy coefficient of nucleons, within the Thomas-Fermi approach and electrons respectively. The last term stands for the potential interaction of the nucleons and the coefficients b_i and a_i has to be obtained by fitting procedure for different RMF parameter sets.

Despite the deprivation of direct experimental measurement or empirically acquirable data for the nuclear properties i.e. incompressibility, symmetry energy etc. of the neutron star, the numerical values calculated here with the help of consolidated RMF and CDFM formalism appear justifiable and irreprochable. The competency of the present theoretical perspective can be exuberantly validated using various consistent energy density functionals and relevant RMF parameter sets. The accomplished accessibility to neutron star properties through a finite nuclei approach favour more dimensions of strongly correlated bridge betwixt the two unequal size objects.

TABLE I: The numerical values of incompressibility, symmetric energy, slope and curvature parameter for maximum mass star of NL3, G3 and IU-FSU parameter sets. The maximum mass for NL3, G3 and IU-FSU parameter sets are $2.850M_\odot$, $2.004M_\odot$ and $1.940M_\odot$ respectively. All the values are in MeV.

Parameter	NL3	G3	IU-FSU
K^{star}	44.845	29.208	29.654
S^{star}	145.948	66.547	59.281
L^{star}_{sym}	614.782	306.971	319.644
K^{star}_{sym}	-689.773	-361.945	-226.740

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