Study of nuclear symmetry energy using relativistic energy density functional approach

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Introduction

The major objective of modern nuclear physics is to understand the variation of structural properties of extreme neutron-proton $(n-p)$ asymmetric nuclear matter. With the increased accessibility of radioactive ion-beam (RIB) facilities around the world, it is now experimentally possible to study the nuclear matter properties of highly asymmetric nuclei with great precision and put to the test the theoretical models. However, it is increasingly difficult to perform extensive experimental measurements on a wide range of highly unstable nuclear matter, which includes astrophysical objects such as neutron stars. In response to the present experimental constraints, modern theoretical formalism such as the non-relativistic Hartree-Fock+BCS approach with Skyrme interaction and relativistic mean-field with different parameter sets provide successful means to study the nuclear matter properties for a wide range of nuclei which are in agreement with the available experimental data [1].

Measurements of nuclear matter densities and collective excitations have aided in understanding some fundamental aspects of the equation of state (EoS); however, the nuclear matter properties associated with the $n-p$ asymmetry of the EoS are largely unexplored as of yet. In recent years the study of isospin-dependence of asymmetric nuclear matter and density-dependent nuclear symmetry energy (NSE) has become prominent on both the theoretical and experimental fronts. The study of NSE serves as the definitive link between finite nuclei and infinite nuclear matter. In the past decade, the non-relativistic Brückner energy density functional energy (Brückner-EDF) has been employed within the coherent density fluctuation model (CDFM) to estimate the surface properties of nuclei. However, the Brückner's-EDF being non-relativistic nature, fails to accurately replicate the empirical saturation point at $\rho \approx 0.2$ fm^{-3} instead of $\rho \approx 0.15$ fm^{-3}, also referred as the Coaster-Band problem [2]. To address this issue, recently, a fitting procedure was introduced [2] having nuclear matter saturation plots obtained from effective-field theory motivated relativistic mean-field (E-RMF) formalism for varying $n-p$ asymmetry with widely used NL3 and recently developed G3 parameters. The present calculation focus on obtaining the surface properties such as symmetry energy along with its surface and volume components for the G3 parameter set using the relativistic-EDF and comparing the same with Brückner's prescription. We perform all the calculations for spherical nuclei of Scandium $(Z=21)$ isotopic chain and study the existence of possible shell and/or sub-shell closure.

Theoretical Formalism

Based on the newly fitted binding energy function of E-RMF can be expressed as [2]:

$$\mathcal{E}(x) = C_k \rho_o^{2/3}(x) + \sum_{i=3}^{14} \left(b_i + a_i \alpha^2\right) \rho_o^{i/3}(x). \quad (1)$$

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Within the CDFM formalism, the symmetry energy is calculated as [1]:

$$S = \int_0^\infty dx |\mathcal{F}(x)|^2 S^{NM}(x). \quad (2)$$

The term $|\mathcal{F}(x)|^2$ implies the weight function obtained from the RMF density of nuclei given as:

$$|\mathcal{F}(x)|^2 = -\left(\frac{1}{\rho_0(x)}\frac{d\rho(r)}{dr}\right)_{r=x}. \quad (3)$$

More details related to the calculation of surface properties within CDFM is given in Refs. [1, 2, 3].

Results and discussion

Using the spherical equivalent RMF densities of Scandium isotopes, we calculate the weight function $|\mathcal{F}(x)|^2$ within the CDFM. The plot of density and weight function with respect to nuclear distance is given in Fig. 1, showing a bell structure with maxima near the center. The density-dependent symmetry energy is estimated along with its volume and surface parts for Relativistic-EDF as given in Fig. 2. On careful observation, one can find evidence of discontinuity or kink at $N = 50$ for both Relativistic-EDF and Brückner's prescription. The discontinuity indicates the existence of possible shell and/or sub-shell closure. It is important to note here that not all kinks point to the existence of shell closure, and it may need experimental validation. Moreover, we find minor kink at $N = 40$ and 46 for Relativistic-EDF but not for Brückner-EDF. The region of $N = 40$ is expected to have a possible shell or sub-shell closure based on the experimental findings close to Calcium-like nuclei such as Titanium [4]. More detailed experimental investigation in this region is highly welcome. The Relativistic-EDF observations are in line with the experimental results and thus indicate its superiority over the Brückner's prescription.

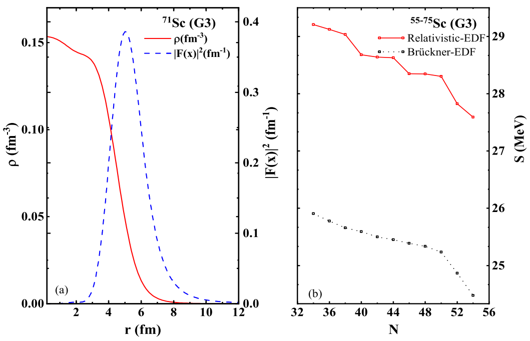

FIG. 1: (a) The spherical RMF density ρ and weight function $|\mathcal{F}(x)|^2$ wrt. distance r, (b) nuclear symmetry energy S wrt. neutron number N for Sc with G3 parameter set.

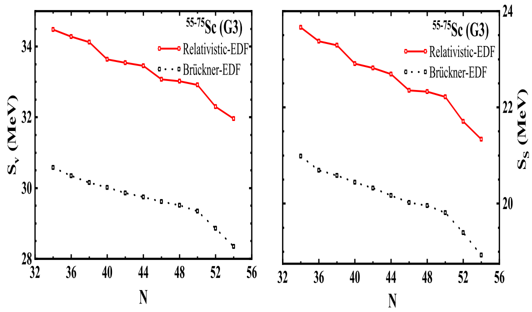

FIG. 2: The calculated symmetry energy components namely, (a) volume S_V and (b) surface S_S, symmetry energy for the Relativistic-EDF and Brückner-EDF is shown with number of neutrons for Scandium isotopes with G3 parameter set.

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