Role of Nuclear Matter Saturation Properties in the Predictions of Finite Nuclei Bulk Properties

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Introduction

The empirical values of nuclear matter (NM) saturation properties, namely, the saturation density ρ_0, energy per particle $e(\rho_0)$, incompressibility $K(\rho_0)$, symmetry energy $E_s(\rho_0)$ and slope of symmetry energy $L(\rho_0)$ are in the range 0.17±0.02 fm^{-3} , -16±0.02 MeV , 240±20 MeV, (27-38) MeV and (35-110) MeV respectively [1]. The uncertainties in the values of $E_s(\rho_0)$ and $L(\rho_0)$ are large and the efforts to constrain their values are an important area of current nuclear research. In the present work our attempt is to search for the probable values of the NM saturation parameters from the study of the bulk properties in finite nuclei. For this purpose we have used the finite range Simple effective interaction (SEI) with Yukawa form.

Formalism

The SEI is given by,

$$V_{eff}(r)=t_0(1+x_0P_\sigma)\delta(\vec{r})+\frac{t_3}{6}(1+x_3P_\sigma)\left(\frac{\rho(\vec{R})}{1+b\rho(\vec{R})}\right)^{\gamma}\delta(\vec{r})+(W+BP_\sigma-HP_\tau-MP_\sigma P_\tau)f(r) \quad (1)$$

where, f(r) is the form factor for the finite range part that depends on a single parameter α, the range of the interaction. In this work, f(r) is taken to be of Yukawa form $\frac{e^{-r/\alpha}}{r/\alpha}$. The SEI contains altogether 11-parameters, namely, ϒ, b, t_0, x_0, t_3, x_3, W, B, H, M and α. Out of these 11 parameters 10-parameters are fixed utilizing the momentum dependence of neutron (n) and proton (p) mean field properties in NM and the density dependence of the nuclear symmetry energy, where it is required to assume only three standard values of NM saturation properties, namely, ρ_0, $e(\rho_0)$ and $E_s(\rho_0)$. In this way all the interaction parameters are fixed, except one, t_0, which is kept open to be determined from the finite nuclei calculations [2, 3]. The parameters thus determined describe the NM properties associated with the momentum and density dependence of n- and p-mean fields in isospin and spin asymmetric NMs well and follow the trends predicted by microscopic calculations [3, 4, 5].

Under the framework of density functional theory (DFT), the energy of a nucleus can be obtained as,

$$E=\int H(\rho_n,\rho_p,\tau_n,\tau_p,J_n,J_p,\nabla\rho_n,\nabla\rho_p)d^3R \quad (2)$$

where, $\vec{R}=\frac{\vec{r_1}+\vec{r_2}}{2}$ is the center of mass co-ordinate of the two interacting nucleons at $\vec{r_1}$ and $\vec{r_2}$. In this expression,

$$H=\frac{\hbar^2}{2m}(\tau_n+\tau_p)+H_d^{Nucl}+H_{exch}^{N}+H^{SO}+H^{Coul} \quad (3)$$

with $\rho_n,\rho_p,\tau_n,\tau_p,J_n,J_p$ being the neutron and proton densities, kinetic energy densities and spin densities, respectively. The expressions of the nuclear direct (exchange) part H_d^{Nucl} (H_{exch}^{N}), spin-orbit H^{SO} and Coulomb H^{Coul} are given in ref.[2], which are valid for a finite range interaction with any conventional functional form factor. The spin-orbit contribution is computed using the zero-range force $V_{ij}^{SO}=iW_0(\sigma_i+\sigma_j)[\vec{k}\times\delta(\vec{r_i},\vec{r_j})\vec{k}]$. It has to be mentioned here that the localization of the exchange energy is performed using the extended Thomas-Fermi (ETF) expansion of the density matrix (DM) [6]. The variational principle applied to E results into a set of Skyrme-like single-particle equations. For open shell nuclei, pairing correlations play a crucial role and they have been included at BCS level using the zero-range density-dependent pairing interaction [7]. The two-body center of mass correction has also been taken into account [2]. The only open parameter of the SEI, t_0, as well as the strength parameter of the SO term W_0, which also enters in the calculation of a finite nucleus, are fixed here from the binding energies (BEs) of the doubly closed nuclei Ca^{40} and Pb^{208}.

Results and Discussion

As the purpose of this work is to examine the role of the NM saturation properties in the prediction of finite nuclei bulk properties, we have chosen the 161-spherical even-even nuclei for which data of BEs, as well as charge radii of 86 out of them, are found in the data tables [2]. In order to start with, we consider three standard values of NM properties, $e(\rho_0)$=-16 MeV, T_{f0}=37 MeV (it corresponds to ρ_0=0.161 fm^{-3}) and $E_s(\rho_0)$=30 MeV for the equation of state (EoS1) with Υ=1/2 (that gives $K(\rho_0)$=238MeV). With this, the calculations of BEs and charge radii for the 161 even-even spherical nuclei are performed. The root mean square (rms) deviation of the theoretical predictions from the experimental data for BEs of the 161 nuclei is obtained as ΔE =8.452 MeV, whereas, that of charge radii of 86-nuclei is Δr =0.056fm. The results of the differences of BEs and charge radii between theory and experimental values are shown in panels (a) and (b) in Figure 1. Now these NM parameters $e(\rho_0)$, ρ_0 and $E_s(\rho_0)$ are varied and for the variation of each NM parameter, the 10-parameters of the NM and t_0 and W_0 in finite nuclei are computed from the beginning following the same procedure so that the prediction in NM remains unchanged, and then the predictions for the 161 nuclei are examined. Performing the analysis for the several such EoSs, each one resulting from the variation of each NM saturation property, it has been found that the EoS for e (ρ_0) = -16.05 MeV, T_{f0}=37.4 MeV, $E_s(\rho_0)$=34MeV of $\gamma = \frac{1}{2}$ (EoS2) predicts the results for BEs of 161 nuclei and charge radii of 86 nuclei with minimum rms deviations, ΔE=1.882 MeV and Δr=0.041fm, respectively, which can be compared with the predictions of any other effective force. The differences in BEs and charge radii for the nuclei for this EoS2 are also shown in panels (a) and (b) of Figure 1. Variation in any of the NM parameters results into deterioration in terms of increasing the rms deviations. For this EoS2, that gives minimum rms deviations, the slope parameter $L(\rho_0)$ is predicted to be 72.7 MeV. The same calculation is repeated for other values of Υ and it has been found that the EoS in each case that gives minimum rms results for ΔE and Δr has $E_s(\rho_0)$=34 MeV and $L(\rho_0)$=72$\pm$1MeV.

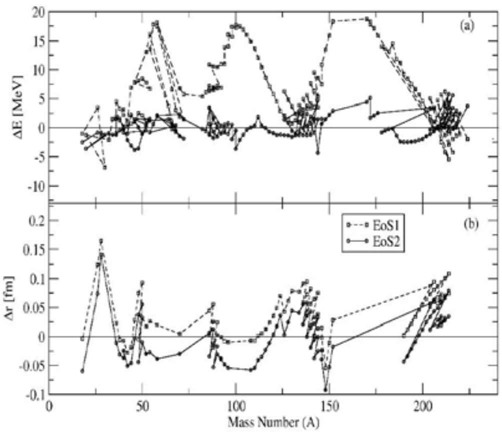

Figure.1 *(a)* ΔE *as a function of mass number A for 161 nuclei (b)* Δr *as a function of mass number A for 86 nuclei, for the two EOSs.*

Summary and Conclusions

From the analysis of the bulk properties of 161-spherical nuclei for the EoSs covering a wide range of Υ, it is found that the EoSs which give minimum rms deviations have values of NM symmetry energy parameter, $E_s(\rho_0)$ =34 MeV and slope parameter, $L(\rho_0)$=72±1 MeV.

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