Study of the Correlation between Neutron skin and Neutron star crust-core transition using Simple effective interaction

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Introduction

Studies on atomic nuclei can provide valuable information about the slope of the symmetry energy parameter, L [1–3] through a nuclides neutron-skin thickness which is defined as the difference between the neutron and proton root mean square radii, $R_{skin} = R_n - R_p$. Heavy nuclei are expected to have a neutron-rich skin. The thickness of the neutron skin depends on the pressure of neutron-rich matter: the greater the pressure, the thicker the skin as neutrons are pushed out against surface tension. The same pressure that supports a neutron star against gravity [2]. The search for a possible connection between the neutron skin in finite nuclei and the crustal thickness in neutron stars (NS) is a subject of contemporary interest[2]. The neutron star crust is crucial for a number of astrophysical observables, such as, glitches in the rotational period of pulsars [4], neutron-star cooling[5], etc. In Ref.[2] an inverse relationship between the stiffness of the equation of state (EoS) and the crustal thickness has been found. It has been shown there that the thicker the neutron skin of a heavy nucleus the lower is the transition density from nonuniform to uniform neutron-rich matter. In this work, we examine the correlation between the neutron skin thickness in neutron-rich isotopes, and the crust-core transition density in NSs by varying the L-value of the EoS. We compute the skin thickness in neutron-rich nuclei for different L-values of the EoS comparing the results with the available experimental range, as well as, with the corresponding predictions of the crust-core transition density in NSs calculated using the dynamical method [6]. The finite range Simple effective interaction (SEI) is used in the study, and the predicted skin thickness is also compared with those of several Skyrme and relativistic mean field (RMF) models.

Formalism

The SEI is given by [7]

$$\begin{aligned} V_{eff} &= t_0(1 + x_0 P_\sigma)\delta(r) \\ &+ \frac{t_3}{6}(1 + x_3 P_\sigma)\left(\frac{\rho(\mathbf{R})}{1 + b\rho(\mathbf{R})}\right)^\gamma \delta(r) \\ &+ (W + BP_\sigma - HP_\tau - MP_\sigma P_\tau)f(r) \\ &+ \text{Spin-orbit part.} \end{aligned} \quad (1)$$

where, $f(r)$ is the finite range form factor, taken to be of Yukawa form here. The SEI in Eq.(1) has 11 numbers of parameters: α, γ, b, x_0, x_3, t_0, t_3, W, B, H, and M and one more parameter, the spin-orbit strength parameter(W_0), enters in the description of finite nuclei (for details of the parameter fixation refer to [8]). The finite nuclei calculations are performed using the so-called Quasi-local Density Functional Theory (QLDFT) together with the BCS pairing. The slope parameter is computed as, $L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho} |_{\rho_0}$, where $E_{sym}(\rho)$ is the symmetry energy at density ρ.

Results and Discussion

The EoS of SEI having $\gamma = 1/2$ is used for which the incompressibility for symmetric nuclear matter is K=240 MeV. Bao An Li[9] upon analyzing the results for different observables studied under different model calculations inferred the ranges for $E_{sym}(\rho_0)$ to be around (31.6 ± 2.66) MeV while the $L(\rho_0)$ in the range (58.9±16) MeV. By analyzing the PREX-II results[10] for skin thickness in ^{208}Pb using the relativistic energy density functionals, Reed et. al [11] have prescribed the range for L =(106±37). Estee et. al.[12], using the charged pion spectra measurement at high transverse momenta, deduced the L-value in the range $42 < L < 117$ MeV which is consistent with PREX II results. Here we have

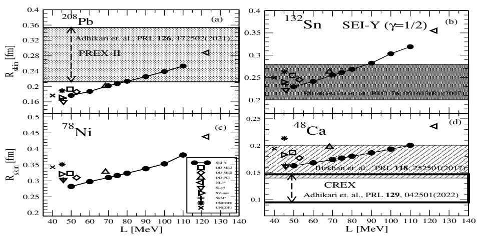

FIG. 1: Variation of R_{skin} with slope(L) using SEI-Y($\gamma = 1/2$) compared with experimental value where available (References mentioned in each panel for the respective nuclei) and with different interaction results [13].

computed the skin thickness using the SEI EoSs having different values of L in the doubly closed nuclei, ^{208}Pb, ^{132}Sn, ^{78}Ni, and ^{48}Ca, and the results are shown in the four panels of Fig.1 together with the probable ranges extracted from various experimental studies, except in case of ^{78}Ni for which experimental data is not available. The PREX-II result for ^{208}Pb [10] in panel(a) prescribes the lower limit of L to be 80 MeV, whereas, the experimental data for ^{48}Ca allows a lower value for L. We have, therefore, taken the variation of L in the range 50-110 MeV. For the sake of comparison, we have also shown the skin thickness results of some of the RMF and non-relativistic interaction sets [13] in the respective figures. With the increase in the slope parameter L, the skin thickness shows a linearly increasing trend in all the four cases implying extended neutron distribution for higher L. The crust-core transition densities for the

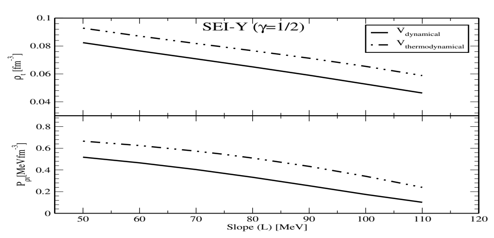

FIG. 2: Variation of transition density(ρ_t) and transition pressure(P_{ρ_t}) with slope L using both the dynamical and thermodynamical methods using SEI-Y ($\gamma = 1/2$).

EoSs of SEI corresponding to the slope values in the range L=80±30 MeV are calculated under the dynamical method. The results of transition density (ρ_t) is obtained in the range 0.0643±0.01805fm^{-3} and transition pressure (P_{ρ_t}) in the range 0.3098±0.2080 $MeVfm^{-3}$. It is worth mentioning here that the dynamical method is more comprehensive and complete, than the often used thermodynamical method, where the surface and Coulomb contributions are included. The L dependence of ρ_t and P_{ρ_t} is shown in the two panels of Fig.2, where one can see the linear decreasing trend for ρ_t, implying a decrease in crustal thickness of the NS, with increase in L.

Conclusion

A stiffer symmetry energy at saturation predicts a larger neutron skin in finite nuclei, and in turn, a thinner neutron star crust. This is in agreement with the earlier findings of [2].

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