Neutron Skin Thickness & Isospin-symmetry breaking

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Introduction

Isospin-symmetry breaking (ISB) terms in the nuclear interaction refer to the deviations from strict isospin symmetry in the strong nuclear force. The ISB terms, though small in magnitude, have garnered considerable attention due to their subtle yet consequential effects in the isobaric analog states. Under perfect charge symmetry, the neutron radius of a nucleus equals the proton radius of its mirror nucleus i.e., $R_n(Z,N) = R_p(N,Z)$. This relationship holds when Coulomb contributions and other charge-dependent effects are switched off. We have examined the isospin breaking effect of the Coulomb interaction by examining the neutron skin in finite nuclei. The finite range simple effective interaction (SEI) is used for the study, whereas, the Coulomb contribution to the nuclear radius has been taken from the Liquid Drop Model (LDM) [1] calculation.

Formalism

The SEI is given by [2]

$$\begin{aligned} V_{eff} &= t_0(1+x_0P_\sigma)\delta(r) \\ &+ \frac{t_3}{6}(1+x_3P_\sigma)\left(\frac{\rho(\mathbf{R})}{1+b\rho(\mathbf{R})}\right)^\gamma \delta(r) \\ &+ (W+BP_\sigma - HP_\tau - MP_\sigma P_\tau)f(r) \\ &+ \text{Spin-orbit part.} \end{aligned} \tag{1}$$

where, $f(r)$ is the finite range form factor, taken here to be of Gaussian form. 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 the spin-orbit strength parameter (W_0).The finite nuclei calculations are performed using the so-called Quasi-local Density Functional Theory (QLDFT) together with the BCS pairing. In this work we have used the equation of state (EoS) of SEI corresponding to γ=0.42 (SEI-G), whose parameters are given in Table I of Ref.[3].

Result and Discussion

The linear relationship between the skin thickness ΔR_{np} in nuclei and the mass number A is influenced by the Coulomb repulsion of the protons. This Coulomb contribution in a nucleus has been computed under LDM $\Delta R_{Coul} \approx -ZA^{-1/3} \times (r_0 c_1/8Q^*)$, where r_0 is the nuclear radius constant, c_1 is the Coulomb energy coefficient ($c_1 = 3e^2/5r_0$), and Q^* is the effective surface stiffness coefficient [4]. Using the values presented in Ref.[1], this contribution can be estimated as $\Delta R_{Coul} \approx -ZA^{-1/3} \times 0.0033$ fm [4]. The Coulomb-subtracted neutron skin thickness ($\Delta R^*_{np} = \Delta R_{np} - \Delta R^{Coul}_{np}$) is shown as a function of isospin asymmetry (δ) in Fig.1 using SEI-G. A linear fit is observed which is given by $\Delta R^*_{np} = 1.2978 \times \delta - 0.0144$ and having a correlation coefficient (r) of 0.9909. The linear fit data of different experimental and theoretical results are taken from Ref.[4] is also shown in Fig.1. The experimental antiprotonic x-ray data ($\Delta R^{*<}_{np}$) is shown as brown shaded region, the proton scattering ($\Delta R^{*>}_{np}$) data as green shaded region, and the *ab initio* coupled cluster (CC) results (ΔR^{*CC}_{np}) as yellow shaded region in the same figure. Our linear fit exhibits a substantial degree of overlap with the experimental data fits of the antiprotonic x-ray experiments, the proton-scattering data, and the *ab initio* coupled cluster predictions. Our slope value of 1.29 is closer to the values of the experimental ones in comparison to the *ab initio* CC prediction. In LDM, this slope is associated with the ratio between the

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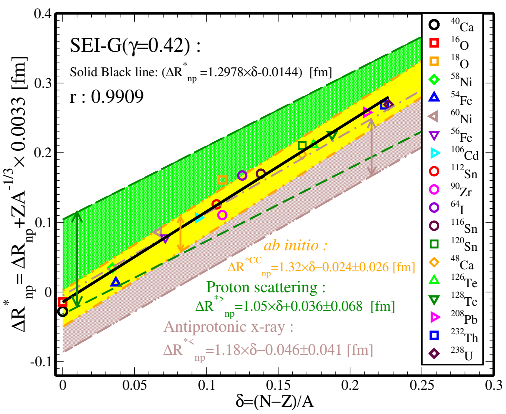

FIG. 1: Coulomb-subtracted neutron skin thickness ($\Delta R^*_{np} = \Delta R_{np} + ZA^{-1/3} \times 0.0033$ fm) plotted as a function of δ for the SEI-G($\gamma = 0.42$) EoS compared with the available experimental data.

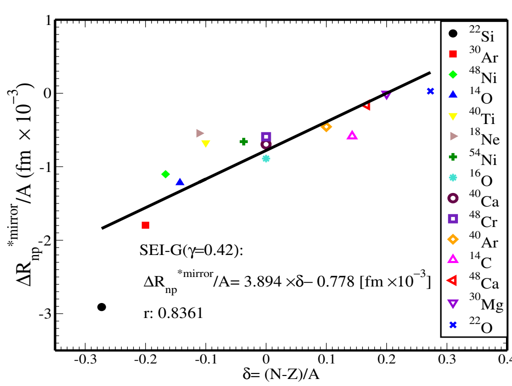

FIG. 2: Coulomb-subtracted mirror neutron skin thickness plotted as a function of the isospin asymmetry for the SEI-G($\gamma = 0.42$) EoS.

symmetry-energy coefficient (J) and the effective stiffness coefficient ($\approx 3r_0 J/2Q^*$).

We now examine the extent of ISB in mirror nuclei pairs for which the point-proton radius, R_p, and its mirror partner's point-neutron radius, R_n^{mirror} should be precisely identical under perfect isospin symmetry, i.e., $\Delta R_{np}^{mirror} = R_n^{mirror} - R_p = 0$. The Coulomb-subtracted mirror neutron skin thickness is given by $\frac{\Delta R_{np}^{*mirror}}{A} = \frac{\Delta R_{np}^{mirror} + ZA^{-1/3} \times 0.0033}{A}$ where, $\Delta R_{np}^{mirror}({}^A_Z X_N) = R_n({}^A_N Y_Z) - R_p({}^A_Z X_N)$. In this instance, the Coulomb-subtracted difference, $\Delta R_{np}^{*mirror}$, is expected to exhibit a proportional relationship with the product of isospin asymmetry and mass number, $\delta \times A$ where the proportionality constant is expressed in terms of nuclear matter incompressibility K as [4],

$$\Delta R_{np}^{*mirror}/A \approx \delta \times (r_0 c_1/K). \quad (2)$$

To examine this relationship, the Coulomb-subtracted difference $\Delta R_{np}^{*mirror}/A$, against the isospin asymmetry, is shown in Fig.2. The Coulomb-subtracted difference is linearly related to isospin asymmetry albeit with a slightly lower correlation coefficient of 0.8361. From the slope value, the nuclear compressibility coefficient is obtained using Eq.2, to be K=221.9 MeV for the SEI-G. This is a reasonably better result as compared to the value 138 MeV obtained in the *ab initio* CC calculation[4].

Conclusion

A strong linear relationship is found between the Coulomb-subtracted neutron skin thickness and the isospin asymmetry. Similar linear correlation is also obtained in case of Coulomb-subtracted neutron skin thickness in mirror pairs. This finding offers a valuable avenue for estimating the neutron radii of rare isotopes.

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