Model dependence in the density content of nuclear symmetry energy

C. Mondal[1],* S. K. Singh[2], B. K. Agrawal[1], M. Centelles[3], G. Colò[4,5], X. Roca-Maza[4,5], N. Paar[6], S. K.Patra[2], and X. Viñas[3]
[1]*Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700064, India*
[2]*Institute of Physics, Bhubhaneshwar, 751005, India*
[3]*Departament d'Estructura i Constituents de la Matèria and Institut de Ciències del Cosmos, Facultat de Física, Universitat de Barcelona, Diagonal 645, E-08028 Barcelona, Spain*
[4]*Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, I-20133 Milano, Italy*
[5]*INFN, sezione di Milano, via Celoria 16, I-20133 Milano, Italy and*
[6]*Physics Department, Faculty of Science, University of Zagreb, Zagreb, Croatia*

Introduction

Apart from very few light nuclei, all nuclear systems in nature, starting from tiny finite nuclei to huge astrophysical objects like neutron stars, are asymmetric. Densities of these systems vary over a wide range. So, accurate knowledge of symmetry energy over a wide range of density is very essential to understand several phenomena in finite nuclei as well as in neutron stars. The density dependence of the nuclear symmetry energy around the saturation density (ρ_0) is described by its density derivative as,

$$L = 3\rho_0 \left(\frac{dS(\rho)}{d\rho} \right)_{\rho_0}, \qquad (1)$$

where, $S(\rho)$ is the symmetry energy at a density ρ. The Droplet Model (DM) suggests that bulk part of the neutron-skin thickness, $\Delta r_{\rm np}^{\rm bulk}$, in a heavy nucleus is linearly correlated to $a_{\rm sym}(A)/J$ [1], where, $J = S(\rho_0)$ and $a_{\rm sym}(A)$ is symmetry energy for finite nuclei. The $a_{\rm sym}(A)$ can be expressed approximately in terms of L [2]. Neutron-skin thickness, $\Delta r_{\rm np}$, in a heavy nucleus calculated for a set of randomly (statistically speaking) selected models show strong correlation between $\Delta r_{\rm np}$ and L. This correlation mainly comes from bulk part of the $\Delta r_{\rm np}$ [3].

*Electronic address: chiranjib.mondal@saha.ac.in

Method

The neutron-skin thickness and several symmetry energy parameters are calculated using four different families of systematically varied models, namely, FSV, TSV, SAMi-J [4] and DDME [5]. The energy density functional associated with FSV, TSV and DDME correspond to an effective Lagrangian density typical of the relativistic mean-field models and that for SAMi-J is based on the standard form of the Skyrme force. These systematically varied parameter sets are obtained so that they explore different values of the symmetry energy parameters around an optimal value, while reasonably keeping the quality of the best fit.

Neutron-skin thickness in a nucleus is defined as,

$$\Delta r_{\rm np} = \langle r_n^2 \rangle^{\frac{1}{2}} - \langle r_p^2 \rangle^{\frac{1}{2}}. \qquad (2)$$

It can be decomposed into bulk and surface part as,

$$\Delta r_{\rm np} = \Delta r_{\rm np}^{\rm bulk} + \Delta r_{\rm np}^{\rm surf}. \qquad (3)$$

In DM, $\Delta r_{\rm np}$ can be expressed in terms of symmtery energy parameters by [1],

$$\Delta r_{\rm np}^{\rm DM} = \sqrt{\frac{3}{5}} \left[\left(\frac{2r_0}{3J}[J - a_{\rm sym}(A)] A^{\frac{1}{3}} (I - I_C) \right) - e^2 \frac{Z}{70J} \right] + \Delta r_{\rm np}^{\rm surf}, \qquad (4)$$

where, the notations carry their usual meaning. One can easily verify that $a_{\rm sym}(A)/J$ is

linearly correlated to $\Delta r_{\rm np}$, provided $\Delta r_{\rm np}^{\rm surf}$ is either small or constant. $a_{\rm sym}(A)$ can be expanded around saturation density as,

$$a_{\rm sym}(A) \approx J - L\epsilon_{\rm A} + \frac{1}{2}K_{\rm sym}\epsilon_{\rm A}^2, \qquad (5)$$

where, $\epsilon_{\rm A} = (\rho_0 - \rho_A)/3\rho_0$.

Results

In Fig. 1, variations of L with $\Delta r_{\rm np}$ and $\Delta r_{\rm np}^{\rm bulk}$ are presented for different families of models. Within each family, L is strongly correlated with both the $\Delta r_{\rm np}$ and $\Delta r_{\rm np}^{\rm bulk}$. It may be noted that, the slopes for the variation in L with $\Delta r_{\rm np}$ and $\Delta r_{\rm np}^{\rm bulk}$ are different for different families of the models. Consequently, when the results for all the families are combined, the correlation becomes weaker.

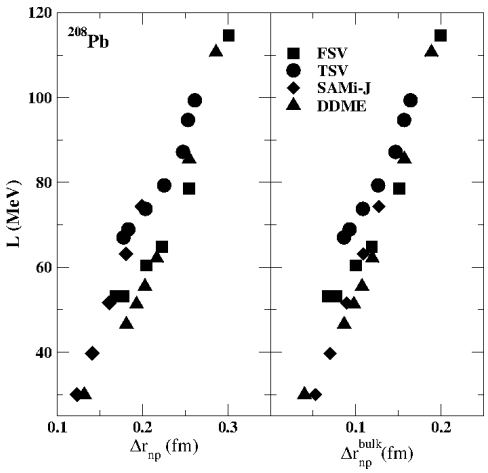

FIG. 1: Plots for the L as a function of $\Delta r_{\rm np}$ (left) and $\Delta r_{\rm np}^{\rm bulk}$(right) for the ^{208}Pb nucleus. The correlation coefficients are 0.941 (left) and 0.954 (right) respectively.

We make a detail comparison between the results for the models belonging to different families, but, yielding almost the same values for the $\Delta r_{\rm np} \approx 0.18$ fm. The various properties of such models from each of the families are compared in Table I. It gives an idea about the spread in the values of different quantities. In other words, it gives a quantitative idea about the amount of model dependence in different symmetry energy parameters. The values of L for these models can differ by about 20 MeV, though, they have $\Delta r_{\rm np} \approx 0.18$ fm. The values of L has a variation of $\sim 15\%$ around its mean value. We also note that, the values of $\epsilon_{\rm A}$ show $\sim 20\%$ variations among the families and the model with largest L possesses the smallest value of $\epsilon_{\rm A}$ and vice versa.

TABLE I: Comparison of the properties of infinite nuclear matter (NM) and of the ^{208}Pb nucleus for four different models. Each of these models yield the neutron-skin thickness in ^{208}Pb close to 0.18 fm. The values for the quantities L, J, and $a_{\rm sym}(A)$ are given in units of MeV and that for the quantities $\Delta r_{\rm np}$, $\Delta r_{\rm np}^{\rm bulk}$ and $\Delta r_{\rm np}^{\rm surf}$ in fm.

		FSV	TSV	SAMi-J	DDME
NM	L	53.19	67.03	63.18	46.50
	J	31.29	31.29	30.00	32.00
^{208}Pb	$a_{\rm sym}(A)$	22.67	22.20	20.35	23.30
	$\Delta r_{\rm np}$	0.178	0.178	0.181	0.181
	$\Delta r_{\rm np}^{\rm bulk}$	0.078	0.086	0.109	0.087
	$\Delta r_{\rm np}^{\rm surf}$	0.100	0.091	0.072	0.094
	$\epsilon_{\rm A}$	0.142	0.120	0.140	0.151

Conclusion

We have shown using a representative set of systematically varied mean models that the correlation of symmetry energy slope parameter with the neutron skin thickness in ^{208}Pb nucleus has a noticeable amount of model dependence. The investigations in order to unveil the source of the model dependence in such correlations are underway.

References

[1] W.D.Myers and W.J. Swiatecki, Ann. Phys. (N. Y.) **55**, 395 (1969).
[2] M. Centelles et al, Phys. Rev. Lett. **102**, 122502 (2009).
[3] M. Centelles et al, Phys. Rev. C **82**, 054314 (2010).
[4] X. Roca-Maza, G. Colò and H. Sagawa, Phys. Rev. C **86**, 031306 (2012).
[5] D. Vretenar, T. Niksic and P. Ring, Phys. Rev. C **68**, 024310 (2003).