The Academic
International Journal of Multidisciplinary Research

An Online Peer Reviewed / Refereed Journal
Volume 3 | Issue 11 | November 2025
ISSN: 2583-973X (Online)
Website: www.theacademic.in

Theoritical study of symmetry energy coefficient and nuclear symmetry energy at saturation density using finite range effective interaction

Mahadeb Pal

Assistant Professor, Department of Physics, SMHGGDCW, Chaksrikrishnapur, Purba Medinipur, West Bengal, India, Email: mpal.phy100@gmail.com

DOI : https://doi.org/10.5281/zenodo.17923154

ARTICLE DETAILS

Research Paper

Accepted: 23-11-2025

Published: 10-12-2025

Keywords:

Droplet model, nuclear symmetry energy, reference density, semi-empirical mass formula.

ABSTRACT

I analyze the relation between the symmetry energy coefficient $a_{sym}(A)$ of finite nuclei with mass number A in the semi-empirical mass formula. The nuclear reference density changes slowly with the mass number and reaches to 0.1 fm^{-3} for heavy nuclei and for light nuclei the reference densities fall rapidly with the decrease of mass number. I also calculate the reference density at ρ_A for a heavy nuclei Pb^{208} and light nuclei Ca^{48} for two different splitting of exchange strength and observed that the reference density slightly higher than 0.1 fm^{-3} for Pb^{208} and slightly lower for Ca^{48}.

Intoduction:

In recent decades, numerous interactions and approaches have been carefully applied to explain the properties of both finite nuclei and infinite nuclear matter including the study of a neutron star. Relativistic Dirac-Bruckner-Hartree-Fock (DBHF) [1-7] and non-relativistic Bruckner-Hartree-Fock (BHF) [8-10], the relativistic mean-field (RMF) [11-12] model, non-relativistic Skyrme-like interactions [13-18] have been used to study the isospin dependent properties of asymmetric nuclear matter such as nuclear symmetry energy, nuclear symmetry potential, the isospin splitting of nucleon effective mass, finite nuclei properties like neutron skin thickness, heavy-ion collision, dipole polarizability, etc., but the theoretical values are varied widely.

The symmetry energy coefficient $a_{sym}(A)$ of finite nuclei and its dependency on nuclear density have drawn significant interest [19-26] due to its usefulness in restricting the density dependence of the nuclear matter symmetry energy [19, 25, 27, 28]. It can be retrieved from extensive experimental data on nuclear structures or directly from the nuclear energy-density functional [19, 29-33], depending upon the approximation. A semi empirical connection between symmetry energy of nuclear matter (NM) at reference density $E_{sym}(\rho_A)$ and the properties of finite nuclei was proposed in [34]. An earlier paper proposed a relationship between the symmetry energy coefficient of finite nuclei and the symmetry energy of NM at reference density [20, 35]. In this paper, I have studied symmetry energy coefficient $a_{sym}(A)$ of finite nuclei with different mass number by using finite range effective interaction and estimate the the symmetry energy at saturation density $E_{sym}(\rho_A)$.

2.1 Finite range effective interaction

The finite range effective interaction is given by [36-37]

$$V_{eff}(r) = t_0\left(1 + x_0 P_\sigma\right)\delta\left(\vec{r}\right) + \frac{t_3}{6}\left(1 + x_3 P_\sigma\right)\rho^{\gamma}\left(\vec{R}\right)\delta\left(\vec{r}\right) + \left(W + B P_\sigma - H P_\tau - M P_\sigma P_\tau\right) f(r) \ , \tag{1}$$

where $f(r)$ represents a short-range interaction of conventional form such as Yukawa, Gaussian, or exponential and specified by single range parameter Λ. $\boldsymbol{\rho} = \boldsymbol{\rho_n} + \rho_p$ is total nucleon density, t_0, t_3, x_0, x_3, γ, W, B, H, M are adjustable parameters in the interaction. This form of effective interaction is very similar to the Skyrme-type of interactions except for the fact that the t_1 and t_2 terms in the latter case have been replaced by the short-range interaction $\left(W + B P_\sigma - H P_\tau - M P_\sigma P_\tau\right) \times f(r)$. $P_\sigma = \frac{1}{2}(1 + \vec{\sigma}_1.\vec{\sigma}_2)$ and $P_\tau = \frac{1}{2}(1 + \vec{\tau}_1.\vec{\tau}_2)$ are the spin and isospin exchange operators respectively. This simple effective interaction is found to have a zero range density-dependent part similar to Skyrme type interaction and long-range density-independent part of conventional form such as Yukawa, Gaussian and exponential. The energy density in the asymmetric nuclear matter (ANM) derived from this effective interaction can be written as,

$$\begin{aligned}H(\rho,\beta)=&\frac{\hbar^2}{2m}\left[\int f_n(\vec{k})k^2d^3k+\int f_p(\vec{k})k^2d^3k\right]\\&+\frac{1}{2}\left[\frac{E_0^{\ l}}{\rho_0}+\frac{E_\gamma^{\ l}}{\rho_0^{\ \gamma+1}}\rho^\gamma\right]\left(\rho_n^{\ 2}+\rho_p^{\ 2}\right)+\left[\frac{E_0^{\ ul}}{\rho_0}+\frac{E_\gamma^{\ ul}}{\rho_0^{\ \gamma+1}}\rho^\gamma\right]\rho_n\rho_p\\&+\frac{E_{ex}^{\ l}}{2\rho_0}\iint\left[f_n(k)f_n(k')+f_p(k)f_p(k')\right]g_{ex}\left(\left|\vec{k}-\vec{k'}\right|\right)d^3k\,d^3k'\\&+\frac{E_{ex}^{\ ul}}{2\rho_0}\iint\left[f_n(k)f_p(k')+f_p(k)f_n(k')\right]g_{ex}\left(\left|\vec{k}-\vec{k'}\right|\right)d^3k\,d^3k',\end{aligned}$$

(2)

$f_\tau\left(\vec{k}\right)$ $(\tau = n, p)$ is the single-particle momentum distribution function normalized to the local density $\rho_\tau = \int f_\tau(\vec{k})d^3\,\vec{k}$.

At zero temperature $f(\vec{k})$ is described by a step function $f(\vec{k}) = \frac{g}{(2\pi)^3}\theta(\vec{k}_f - \vec{k})$, where g is the spin-isospin degeneracy factor and $k_f = \left(\frac{3\pi^2}{2}\rho\right)^{\frac{1}{3}}$ is the Fermi momentum. $g_{ex}\left(\left|\vec{k}-\vec{k'}\right|\right)$ is the normalized Fourier transform of the short-range interaction $f(r)$ and for Yukawa form of functional $f(r)$ it is explicitly given as

$$g_{ex}\left(\left|\vec{k}-\vec{k'}\right|\right) = \frac{1}{1+\frac{\left|\vec{k}-\vec{k'}\right|^2}{\Lambda^2}}.$$

The parameters $E_0{}^l$,$E_0{}^{ul}$, $E_\gamma{}^l$, $E_\gamma{}^{ul}$, $E_{ex}{}^l$and $E_{ex}{}^{ul}$ are related to the interaction parameters as given in Ref. [38]

$$E_0^l = \rho_0\left[\frac{t_0}{2}(1-x_0) + \left(W+\frac{B}{2}-H-\frac{M}{2}\right)\int f(r)d^3r\right], \tag{3.a}$$

$$E_0^{ul} = \rho_0\left[\frac{t_0}{2}(2+x_3) + \left(W+\frac{B}{2}\right)\int f(r)d^3r\right], \tag{3.b}$$

$$E_\gamma^l = \frac{t_3}{12}\rho_0^{\gamma+1}(1-x_3), \tag{3.c}$$

$$E_{\gamma}^{ul} = \frac{t_3}{12}\rho_0^{\gamma+1}(2 + x_3), \tag{3.d}$$

$$E_{ex}^{l} = \rho_0\left(M - \frac{W}{2} - B + \frac{H}{2}\right)\int f(r)d^3r, \tag{3.e}$$

$$E_{ex}^{ul} = \rho_0\left(M + \frac{H}{2}\right)\int f(r)d^3r, \tag{3.f}$$

2.2 Fixation of parameters

The complete calculation of neutron-proton mean-field properties, as well as the equation of state of ANM, requires the correct splitting of the parameters like $\left(E_0{}^{l} + E_0{}^{ul}\right)$, $\left(E_{\gamma}{}^{l} + E_{\gamma}{}^{ul}\right)$ and $\left(E_{ex}{}^{l} + E_{ex}{}^{ul}\right)$ into two specific channels for interactions between like and unlike nucleons. There are no such experimental/empirical constraints on the splitting of these three combined parameters except for the value of nuclear symmetry energy $E_{sym}(\rho_0)$ at normal nuclear matter density from the liquid-drop model. Different choices of these splitting, therefore, lead to contradicting behavior of the iso-vector part of the nuclear mean-field as well as the effective mass. The six parameters $\boldsymbol{E_0{}^{l}}$, $\boldsymbol{E_0{}^{ul}}$, $\boldsymbol{E_{\gamma}{}^{l}}$, $\boldsymbol{E_{\gamma}{}^{ul}}$, $\boldsymbol{E_{ex}{}^{l}}$ and $\boldsymbol{E_{ex}{}^{ul}}$ are related to $\boldsymbol{E_0}$, $\boldsymbol{E_{\gamma}}$ and $\boldsymbol{E_{ex}}$ as in Ref. [36]

$$\boldsymbol{E_0 = \frac{E_0{}^{l} + E_0{}^{ul}}{2},\ E_{\gamma} = \frac{E_{\gamma}{}^{l} + E_{\gamma}{}^{ul}}{2},\ E_{ex} = \frac{E_{ex}{}^{l} + E_{ex}{}^{ul}}{2}}.$$

The parameters $\boldsymbol{E_{ex}}$ and $\boldsymbol{\Lambda}$ are determined to give a correct momentum dependence of the mean-field in SNM at normal nuclear density $\boldsymbol{\rho_0}$ and at zero temperature as demanded by the optical model fits nucleon- nucleus scattering data at intermediate energies [39]. $\boldsymbol{E_0}$, $\boldsymbol{E_{\gamma}}$ and $\boldsymbol{\gamma}$ are determined from the saturation properties, $E(\rho_0)$=-16MeV, $\boldsymbol{\rho\frac{dE(\rho)}{d\rho}\Big|_{\rho=\rho_0} = 0}$ and $K(\rho_0)$=210 MeV as cited in Ref. [36]. Keeping the range parameter, the same, we have considered two different sets of strength parameters for the exchange interaction, and the values of all the parameters are shown in Table 1.

A1: $E_{ex}{}^{l} = \frac{E_{ex}}{2}$, A2: $E_{ex}{}^{l} = \frac{3E_{ex}}{2}$

B1 : $E_{ex}{}^{l} = \frac{E_{ex}}{3}$, B2 : $E_{ex}{}^{l} = \frac{5E_{ex}}{3}$

TABLE: 1 sets of Interaction parameters

Set	$\boldsymbol{E_{ex}{}^{l}}$	$\boldsymbol{E_{ex}{}^{ul}}$	$\boldsymbol{E_{\gamma}{}^{l}}$	$\boldsymbol{E_{\gamma}{}^{ul}}$	$\boldsymbol{E_0{}^{l}}$	$\boldsymbol{E_0{}^{ul}}$	$\boldsymbol{t_3}$ **(MeV)**	$\boldsymbol{\gamma}$	$\boldsymbol{\Lambda}$

	(MeV)	(MeV)	(MeV)	(MeV)	(MeV)	(MeV)			(fm^{-1})
A1	**- 64.599**	**-193.799**	**127.255**	**255.866**	**- 112.5**	**- 199.7**	**13270.998**	**0.181**	**2.363**
A2	**- 193.799**	**-64.599**	**127.255**	**255.866**	**- 23.67**	**- 288.53**			
B1	**- 43.066**	**-215.333**	**127.255**	**255.866**	**- 127.31**	**- 184.89**			
B2	**-215.333**	**-43.066**	**127.255**	**255.866**	**- 8.863**	**- 303.336**			

2.3 Nuclear matter symmetry energy and symmetry energy coefficient in semi-empirical mass formula

The total energy per nucleon for nuclear matter is given by upto 2nd order of isospin asymmetry β as

$$E(\rho,\beta) = E_0(\rho_0) + E_{sym}(\rho)\beta^2 + O(\beta^4), \quad (4)$$

where $\rho = \rho_n + \rho_p$ is the total baryon density with ρ_n & ρ_p denoting the neutron and proton densities respectively. $E_0(\rho) = E(\rho, \beta = 0)$ is the binding energy per nucleon in symmetric nuclear matter and $E_{sym}(\rho)$ be the symmetry energy which is expressed as

$$E_{sym}(\rho) = \frac{1}{2\rho_0}\frac{\delta^2 E(\rho,\beta)}{\delta\beta^2}\Big|_{\beta=0}$$

$$= E_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2!}\chi^2 + O(\chi)^3, \quad (5)$$

where $\chi = \frac{\rho-\rho_0}{3\rho_0}$.

The coefficient $L = 3\rho_0 \frac{dE_{sym}(\rho)}{d\rho}\Big|_{\rho=0}$ and $K_{sym} = 9\rho_0^2 \frac{d^2E_{sym}(\rho)}{d\rho^2}\Big|_{\rho=0}$ are slope and curvature parameters of the symmetry energy respectively. To get the information on the density dependence of symmetry energy, the symmetry energy of finite nuclei has been widely investigated by fitting ground state masses using the liquid drop mass formula.The density dependence of nuclear symmetry energy obtained from the two sets of parameters [39-40] is depicted in fig.1. The experimental result [41] has also been plotted in the same figure for the sake of comparison.

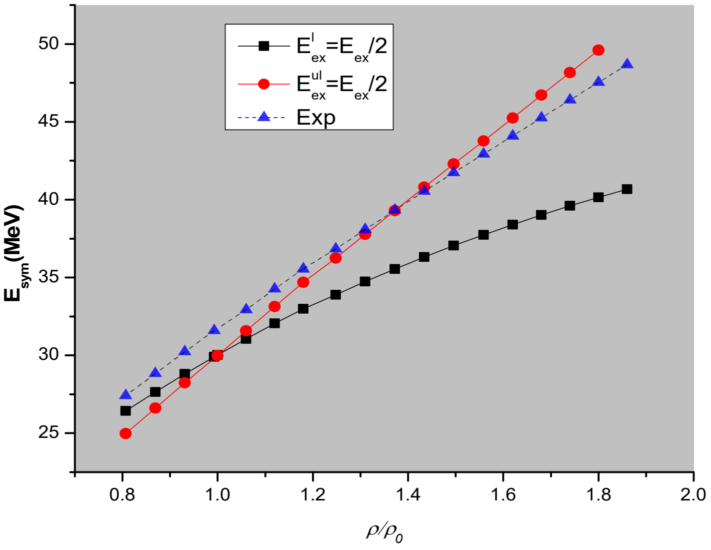


Fig.1. Variation of symmetry energy E_{sym} with density by using our model parameters and an experimental comparison.

The Leptodermous expansion in terms of powers of $A^{-1/3}$, the symmetry energy coefficient $a_{sym}(A)$ of a finite nucleus is written as,

$$a_{sym}(A) = E_{sym}(\rho_0) - e_{ss}A^{-1/3} + e_{cs}A^{-2/3}, \tag{6}$$

Where $E_{sym}(\rho_0)$ denotes the symmetry energy of nuclear matter at normal density, e_{ss} and e_{cs} are the coefficients of the surface-symmetry energy and curvature-symmetry energy terms, respectively. On the basis of the constraints obtained from the different studies of nuclear matter symmetry energy, Centelles et. al. [42] found that symmetry energy coefficient $a_{sym}(A)$ of finite nuclei with mass number A in the semi-empirical mass formula can approximately equal to nuclear matter symmetry energy at reference density ρ_A in the subsaturation density region .i.e.

$$E_{sym}(\rho_A) = a_{sym}(A) \tag{7}$$

Using the semi-empirical mass formula the mass dependence of the symmetry energy coefficient $a_{sym}(A)$ of finite nuclei can be expressed as

$$a_{sym}(A) = \frac{E_{sym}(\rho_0)}{[1+x_A]}, \tag{8}$$

where $X_A = \frac{9E_{sym}(\rho_0)}{4Q} A^{-1/3}$. (9)

The parameter Q is called the neutron skin stiffness coefficient of droplet model (DM) [43-44] and it is related to the nuclear surface symmetry energy [44]. Usually for a given nuclear interaction, the Q parameter can be obtained from asymmetric semi-infinite nuclear matter. The X_A can be approximated by

$$X_A = \left(L - \frac{K_{sym}}{12}\right) \frac{A^{-1/3}}{E_{sym}(\rho_0)}. \quad (10)$$

Using the phenomenological effective interaction [40] and Yukawa form of exchange interaction, X_A is calculated for the splitting of E_{ex}^{l} and E_{ex}^{ul} [45] by using equation (10). Further using these values of X_A in equation (8), I have calculated the values of the symmetry energy coefficient $a_{sym}(A)$ of finite nuclei for E_{ex}^{l} and E_{ex}^{ul}. Using this result one can estimate the symmetry energy at reference density $E_{sym}(\rho_A)$ proposed by Centelles et al. in ref. [46].

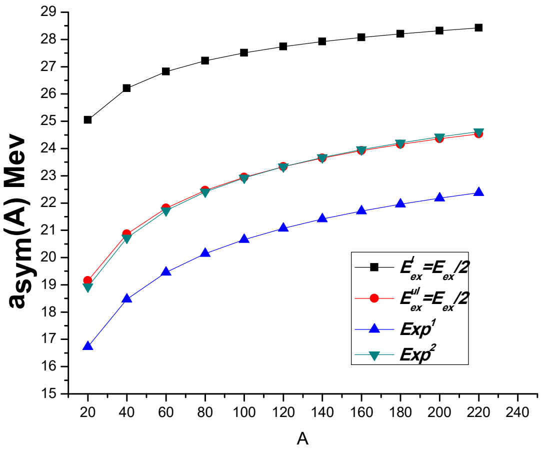


Fig.2. Plot of $a_{sym}(A)$ against A considering saturation density for two sets of interactions as well as some experimental results.

It is observed that when ${E_{ex}}^{l}$ is greater than ${E_{ex}}^{ul}$ the value of $a_{sym}(A)$ lies within 25-28 MeV and when ${E_{ex}}^{ul}$ is greater than ${E_{ex}}^{l}$ it lies within 19-24 MeV for 20<A<240 [47]. It is also observed that when ${E_{ex}}^{ul}$ is greater than ${E_{ex}}^{l}$ the result is approximately experimental result.

According to research in intermediate heavy ion collision (HIC) the density dependent nuclear symmetry energy at subnormal densities [19-23] can be written as

$$E_{sym}(\rho) = E_{sym}(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\alpha} \quad . \tag{11}$$

Now inserting equation (7), (8) and (10) in equation (11) one can obtain

$$\left(\frac{\rho}{\rho_0}\right)^{\alpha} = \left(1 + X_A A^{-1/3}\right)^{-1}. \tag{12}$$

Using equation (12) the reference density ρ_A of a nucleus with mass A can be expressed as

$$\rho_A = \frac{\rho_0}{(1+X_A A^{-1/3})^{\frac{1}{\alpha}}}. \tag{13}$$

From equation (13) the reference density ρ_A is plotted as a function of nuclear mass A for various values of X_A and α in fig.3. In the same figure, the result of the parameterized expression of $\rho_A = \rho_0 - \frac{\rho_0}{(1+cA^{1/3})}$ proposed by Centelles et al. [46] is also shown for comparison.

It is found from the graph that the reference densities for finite nuclei with A=20-250 lies within the range $0.4\rho_0 \leq \rho_A \leq 0.63\rho_0$ for the different values of $E_{ex}{}^{l}$ using equation (13) as well as for the relation proposed in Ref. [42, 46]. It is further observed that the reference densities obtained from the different splitting of $E_{ex}{}^{l}$ as well as the results proposed by Centelles et al. [46] are in good agreement with each other.

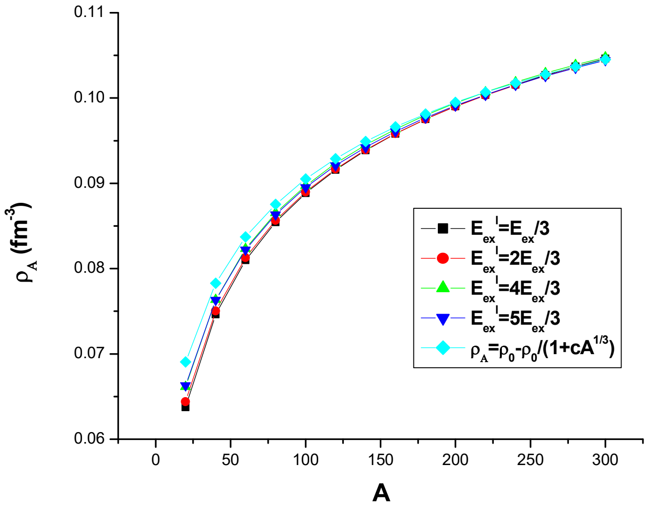


Fig.3: Reference density ρ_A as a function of mass no. A for parameter A1, A2, B1 and B2 as well as for the relation $\rho_A = \rho_0 - \frac{\rho_0}{(1+cA^{1/3})}$.

Centelles et al. tested the parameterization of the above expression in the mass region $40 \leq A \leq 208$. For mass region $A < 40$ and $A > 208$ all the results shows similar extrapolation. It also be noted from fig. 3 that for heavy nuclei the reference densities change slowly with the mass number and reaches to 0.1 fm^{-3}

and for light nuclei the reference densities fall rapidly with the decrease of mass number. So the symmetry energy of nuclear matter at reference density more appreciably related to the symmetry energy coefficient of heavy nuclei than that of lighter nuclei.

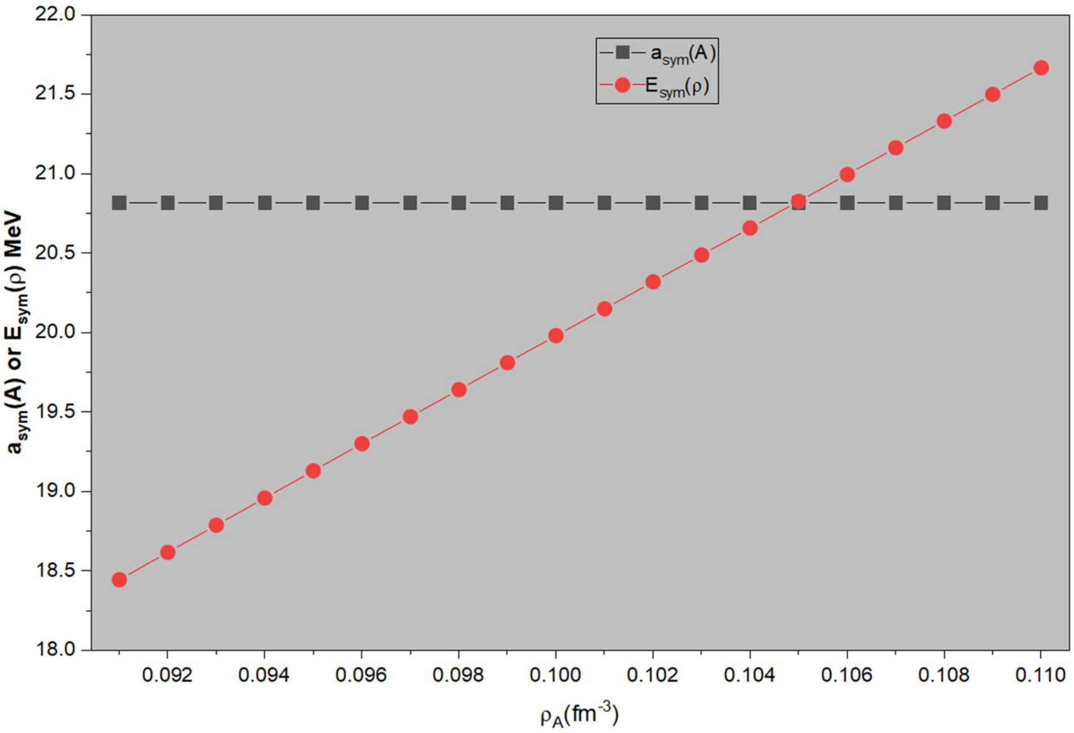
2.4 Reference density of Pb^{208} and Ca^{48}

To verify the reference density ρ_A for particular nuclei, I have also studied the variation of symmetry energy $E_{sym}(\rho)$ and symmetry energy coefficient $a_{sym}(A)$ for two nucleus Pb^{208} and Ca^{48} and plotted the variation in fig.4 and fig.5 respectively.

In fig.4a and fig.4b symmetry energy $E_{sym}(\rho)$ and symmetry energy coefficient $a_{sym}(A)$ for Pb^{208} plotted as a function of reference density ρ_A for interaction A_1 and A_2 respectively and from the fig.4a it is observed that at $\rho_A = 0.106$ fm^{-3}, $E_{sym}(\rho_A) = a_{sym}(A)$ where as from fig.4b reference density ρ_A is about 0.109 fm^{-3}.

On the similar way, I have plotted symmetry energy $E_{sym}(\rho)$ and symmetry energy coefficient $a_{sym}(A)$ for Ca^{48} as a function of reference density ρ_A for interaction A_1 and A_2 respectively in fig.5a and fig.5b and estimate the reference densities are $\rho_A = 0.089$ fm^{-3} for A_1 and 0.091 fm^{-3} for A_2 when $E_{sym}(\rho_A) = a_{sym}(A)$.

Fig.



4a:Variation of $E_{sym}(\rho)$ and $a_{sym}(A)$ for Pb^{208} plotted as a function of reference density ρ_A for interaction A_1.

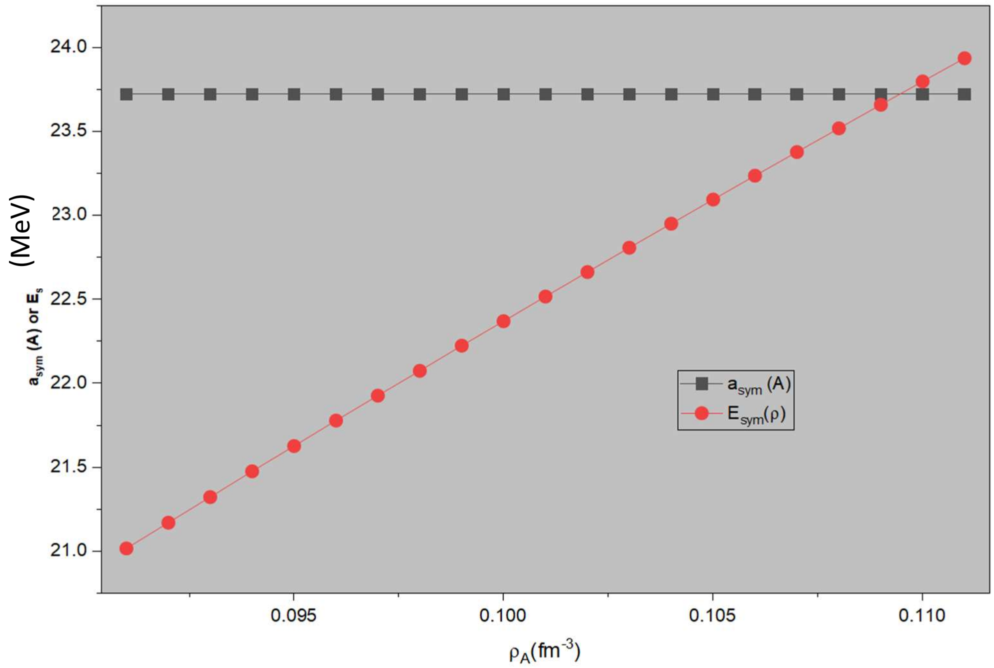


Fig. 4b: Variation of $E_{sym}(\rho)$ and $a_{sym}(A)$ for Pb^{208} plotted as a function of reference density ρ_A for interaction A_2.

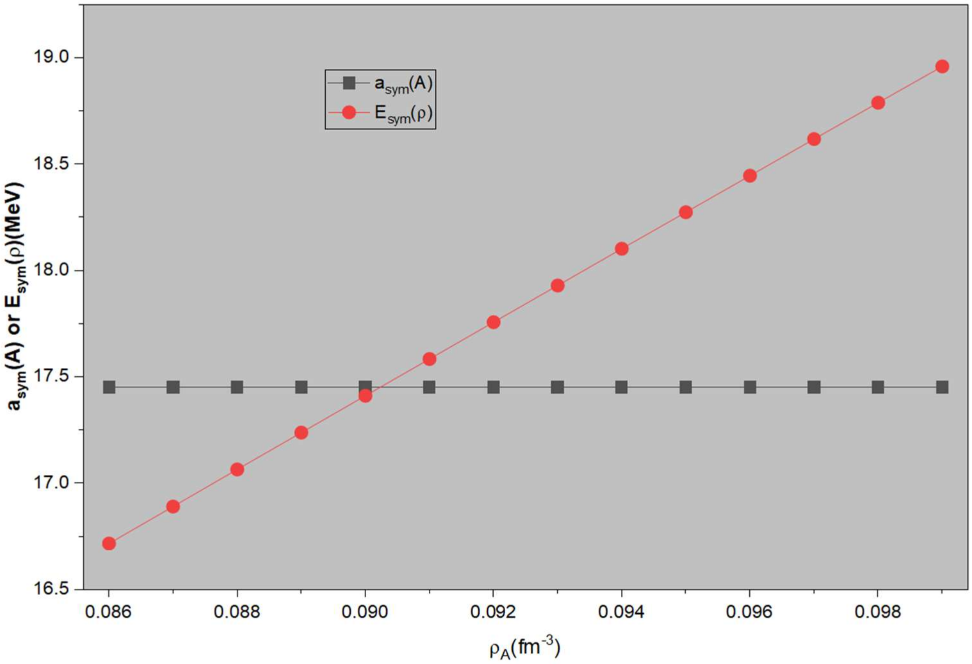


Fig. 5a: Variation of $E_{sym}(\rho)$ and $a_{sym}(A)$ for Ca^{48} plotted as a function of reference density ρ_A for interaction A_1.

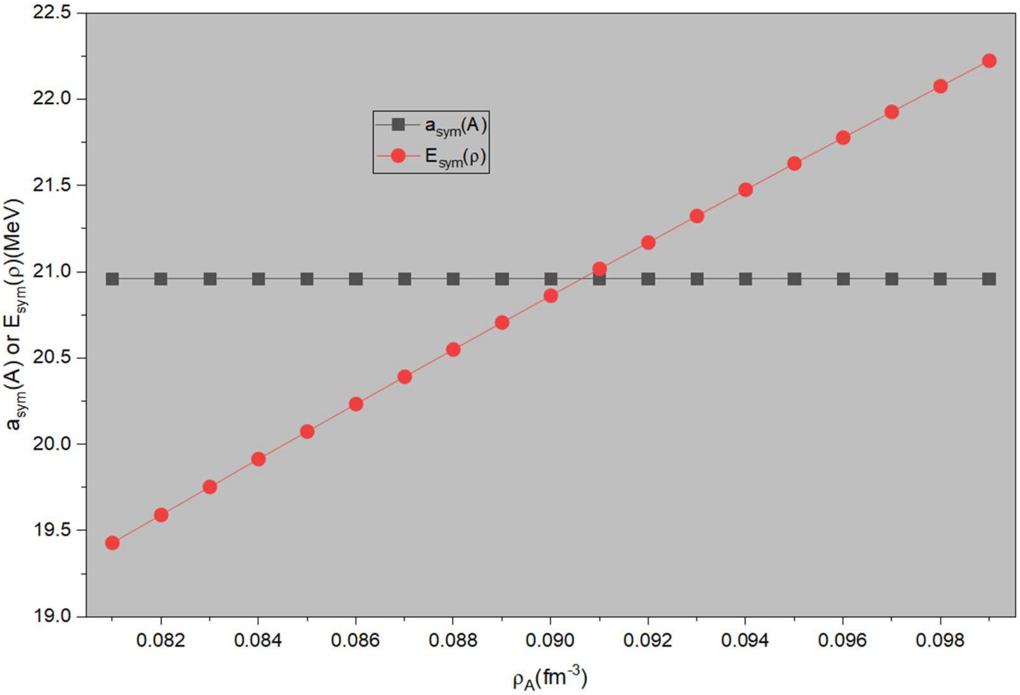


Fig. 5b: Variation of $E_{sym}(\rho)$ and $a_{sym}(A)$ for Ca^{48} plotted as a function of reference density ρ_A for interaction A$_2$.

3. Conclusions

In my study, it is observed that when ${E_{ex}}^{l}$ is greater than ${E_{ex}}^{ul}$ the value of $a_{sym}(A)$ lies within 25-28 MeV and when ${E_{ex}}^{ul}$ is greater than ${E_{ex}}^{l}$ it lies within 19-24 MeV for 20<A<240 [20, 21]. It is also observed that when ${E_{ex}}^{ul}$ is greater than ${E_{ex}}^{l}$ the result is approximately experimental result.

The reference densities for finite nuclei with A=20-250 lies within the range $0.4\rho_0 \leq \rho_A \leq 0.63\rho_0$ for the different values of ${E_{ex}}^{l}$ using equation (13) as well as for the relation proposed in Ref. [12] . It is further observed that the reference densities obtained from the different splitting of ${E_{ex}}^{l}$ as well as the results proposed by Centelles et al. [12] are in good agreement with each other.

I have also studied the variation of symmetry energy $E_{sym}(\rho)$ and symmetry energy coefficient $a_{sym}(A)$ for two nucleus Pb^{208} and Ca^{48}. It is observed that for Pb^{208} nuclei at $\rho_A = 0.106$ fm^{-3}, $E_{sym}(\rho_A)$ = $a_{sym}(A)$ for A$_1$ and reference density ρ_A is about 0.109 fm^{-3} for A$_2$. Similarly for Ca^{48} the reference densities are $\rho_A = 0.089$ fm^{-3} for A$_1$ and 0.091 fm^{-3} for A$_2$ at which $E_{sym}(\rho_A) = a_{sym}(A)$.

In future, there are several ways through which one can extend the work and find some universal data to reduce the controversies about some nuclear matter properties like neutron skin thickness, dipole polarizability etc.

References:

1. E. N. E van Dalen, C. Fuchs and A. Faessler, Nucl. Phys. A 741, 227 (2004).
2. Z. Y. Ma, J. Rong, B. Q. Chen, Z. Y. Zhu and H. Q. Song, Phys. Lett. B 604, 170 (2004).
3. F. Sammarruca, W. Barredo and P. Krastev, Phys. Rev. C 71, 064306 (2005).
4. E. N. E van Dalen, C. Fuchs and A. Faessler, Phys. Rev. Lett. 95,022302 (2005).
5. E. N. E van Dalen, C. Fuchs and A. Faessler, Phys. Rev. C 72, 065803 (2005).
6. J. Rong, J. Z. Y. Ma and G. N. Van, Phys. Rev. C 73, 014614 (2006).
7. I. Bombaci, and U. Lombardo, Phys. Rev. C 44, 1892 (1991).
8. W. Zuo, L. G. Cao, B. A. Li, U. Lombardo and C. W. Shen, Phys. Rev. C 72, 014005 (2005).
9. Z. H. Li et al., Phys. Rev. C 74, 047304 (2006).
10. Z. Z. Ren, F. Tai and D. H. Chen, Phys. Rev. C 66, 064306 (2002).
11. L. W. Chen, C. M. Ko and B. A. Li, Phys. Rev. C 76, 054316 (2007).
12. C. B. Das, S. Das Gupta, C. Gale and B. A. Li, Phys. Rev. C 69, 011603 (2004).
13. L. W. Chen, C. M. Ko and B. A. Li, Phys. Rev. C 69, 054606 (2005).
14. J. Rizzo et al., Nucl. Phys. A 732, 202 (2004).
15. J. Rizzo, M. Colonna and M. Di Toro, Phys. Rev. C 72, 064609 (2005).
16. B. A. Li, Phys. Rev. C 69, 064602 (2004).
17. B. Behra et al., Nucl. Phys. A 753, 367 (2005).
18. J. D. Walecka, Ann. Phys., 83, 491 (1974).
19. B. A. Li, L. W. Chen and C. M. Ko , Phys. Rep. , 464, 113 (2008).
20. L. W. Chen, C. M. Ko and B. A. Li , Phys. Rev. C 72, 064309 (2005).
21. D. V. Shetty, S. J. Yennello and G. A. Souliotis , Phys. Rev. C 76, 024606 (2007).
22. M. A. Famiano et al. , Phys. Rev. Lett. , 97, 052701 (2006).
23. L. W. Chen, C. M. Ko and B. A. Li , Phys. Rev. Lett. , 94, 032701 (2005).
24. S. Chakraborty, B. Sahoo and S. Sahoo , Phys. Atom. Nucl. , 78, 43 (2015).
25. S. Chakraborty, B. Sahoo and S. Sahoo , Int. J. Mod. Phys. , E 21, 1250079 (2012)..
26. M. Pal, S. Chakraborty, B. Sahoo and S. Sahoo , DAE Symp. Nucl. Phys. , 62, 152 (2017).
27. S. Chakraborty, B. Sahoo and S. Sahoo , Int. J. Mod. Phys. E , 27, 1850049 (2018).

28. R. Wang and L. W. Chen, Phys. Lett. B , 773, 10(2017).
29. P. Danielewicz , Nucl. Phys. A , 727, 233 (2003).
30. C. Xu, B. A. Li, L.W. Chen and C. M. Ko , Nucl. Phys. A, 865, 1 (2011).
31. B. A. Li et al. , Progress in Particle and Nuclear Physics , 99, 29-119 (2018).
32. B. Sahoo, S. Chakraborty, and S. Sahoo , Phys. Atom. Nucl. , 79, 1-10 (2016).
33. C. Xu, B. A. Li, and L.W. Chen , Phys. Rev. C , 82, 054607 (2010).
34. R. Chen, B.J. Cai, L.W. Chen, B. A. Li, X. H. Li and C. Xu , Phys. Rev. C , 85, 024305 (2012).
35. C. Xu, B. A. Li and L.W. Chen , E. Phys. J. , A 50, 21 (2014)..
36. B. Sahoo, S. Chakraborty, and S. Sahoo , Phys. Atom. Nucl. 79, 1-10 (2016).
37. B. Behera, T. R. Routray, B. Sahoo, R. K. Satpathy , Nucl. Phys. A , 699, 770 (2002), B. Behera, T. R. Routray, A. Pradhan, S. K. Patra, P. K. Sahu , Nucl. Phys., A 753, 367 (2005).
38. B. Behera, T. R. Routray, A. Pradhan, S. K. Patra and P. K. Sahu , Nucl. Phys. , A 794, 132 (2007).
39. J. Piekarewicz et al. , Phys. Rev. C , 85, 041302(R) (2012).
40. S. Chakraborty, B. Sahoo and S. Sahoo , Nucl. Phys. , A 912, 31 (2013).
41. D. V. Shetty, S. J. Yennello, and G. A. Souliotis , Phys. Rev. C 75, 034602 (2007).
42. T. Sil, M. Centelles, X. Vi˜nas and J. Piekarewicz , Phys. Rev. , C 71, 045502 (2005); M. Warda, X. Vi˜nas, X. Roca-Maza and M. Centelles, Phys. Rev. C 80, 024316 (2009).
43. W. Myers and W. Swiatecki Ann. Phys. 84, 186 (1974).
44. W. Myers , Droplet Model of Atomic Nuclei (Plenum, New York, 1977).
45. S. Chakraborty, S. Mohanta, B. Sahoo and S. Sahoo , DAE Symp. Nucl. Phys., 59, 154 (2014).
46. M. Centelles, X. Roca-Maza, X. Vi˜nas and M. Warda, Phys. Rev. Lett. 102, 122502 (2009).
47. M. Pal, S. Chakraborty, B. Sahoo and S. Sahoo, Int. J. Mod. Phys. E 27, 1850049 (2018).