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Egypt. J. Phys. **Vol. 49,** pp. 65-71 (2021)

Egyptian Journal of Physics
https://ejphysics.journals.ekb.eg/

Neutron Skin Thickness of the Even-Even $^{124-208}$Sm Isotopes

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EVERYTHING in the universe is made up of atoms, which are mediated by the nucleus. The understanding of the complex structure of the nucleus of atoms is still one of the major challenges. Therefore, the physics of rich neutron nuclei is one of the most subjects in nuclear structure physics both theoretically and experimentally. The Hartree-Fock-Bogolyubov (HFB) theory has a good theoretical framework for describing these nuclei since it is generalized the Hartree-Fock approximation with BCS pairing theory. In this work, the neutron skin thickness and neutron distribution, proton and neutron radiiof the even-even $^{124-208}$Sm (Z=62) isotopes were calculated in the framework of the HFB calculations with three different Skyrme type effective nucleon-nucleon interaction: SKI3, HFB9, UNE1 and Gognyforce of typeD1S. In view of existing different type of models and interactions, the question remains which of them provide the best description of data. Our calculated values were compared with the available experimental and theoretical results, where good agreements were obtained.

Keywords: Hartree-Fock-Bogoliubov method; Sm isotopes, Neutron skin thickness; Neutron distribution.

Introduction

The development of experimental tools supports us to investigate the nuclear structure characteristics of an extended area of nuclei in the nuclear landscape [1, 2],which requires searching for a theoretical model that can describe the results. In recent years, many theoretical approaches have been carried out by several groups to investigate their nuclear structure properties. Nowadays, the investigation of nuclear structure towards the drip line has become a hot research topic. Near the drip-line, nuclei which they have low binding energies, present various fascinating aspects like neutron skin, halo, etc. For neutron skin in ^{208}Pb, the experimental data are observed through several methods [3–7] in recent years. Theoretically, neutron skin thickness has been prophesied for a wide range of nuclei with the assistant of several models [8–11]. Moreover, near to the dripline, neutron-rich nuclei have high importance in stellar nucleosynthesis[12, 13].

Nuclear size, radii and mass are the principal quantities applied to probe the nucleus structure. Regardless of these, the investigation of the spectroscopic properties of nuclei also produces an effective tool to examine the nuclear structure properties experimentally.

The description of nuclei near the drip lines needs a framework in which pairing correlation has much interest. Mean-field and pairing in HFB theory are given similar rank and how getting into description the coupling of bound states to the continuum. Thus HFB-formalism gets relieved of the particle gas nearby the nuclei which appears when using Bardeen-Cooper-Schrieffer (BCS) theory [14], which describes the pairing interaction between nucleons in the nucleus. Moreover, two different bases have been used to solve the equation of HFB approach, Harmonic oscillator (HO) and Transformed harmonic oscillator (THO).The normal mode of explaining HFB equation in configurational space is to develop the nucleon wave function of quasi-particle in a suitable total set of single-particle basis.

In this paper, the neutron skin thickness and neutron distribution, proton and neutron radii of the even and even $^{124-208}$Sm (Z=62) isotopes

[*]Corresponding author: alitaqibayati@yahoo.com
DOI :10.21608/ejphysics.2020.42243.1053
Received : 10/9/2020; accepted : 10/10/2020

to be calculated in the framework of the HFB calculations with three different Skyrme types effective nucleon-nucleon interaction: Skyrme types SKI3, HFB9, UNE1 and Gogny force of type D1S. In view of existing different type of models and interactions, the question remains which of them provide the best description of data. Our calculationto be compared with the available results.

Formalism

The Hamiltonian of a two-body fermion system is given by [15],

$$H = \sum_{k_1 k_2} t_{k_1 k_2}\, \hat{c}^{\dagger}_{k_1} \hat{c}_{k_2} + \frac{1}{4} \sum_{k_1 k_2 k_3 k_4} \bar{v}_{k_1 k_2 k_3 k_4}\, \hat{c}^{\dagger}_{k_1} \hat{c}^{\dagger}_{k_2} \hat{c}_{k_3} \hat{c}_{k_4} \quad (1)$$

Where $\hat{c}^{\dagger}$ and $\hat{c}$ are creation and annihilation operators. The first part t corresponds to the kinetic energy and second part$\bar{v}_{k_1 k_2 k_3 k_4} = \langle k_1 k_2 | V | k_3 k_4 - k_4 k_3 \rangle$

are two body anti-symmetrized matrix-elements.

The quasi-particle operators $(\hat{\beta}, \hat{\beta}^{\dagger})$ are related to the particle operators$(\hat{c}, \hat{c}^{\dagger})$ via a linear Bogolyubov transformation,

$$\begin{pmatrix} \beta \\ \beta^{\dagger} \end{pmatrix} = \begin{pmatrix} U^{\dagger} & V^{\dagger} \\ V^{T} & U^{T} \end{pmatrix} \begin{pmatrix} c \\ c^{\dagger} \end{pmatrix}, \quad (2)$$

where$U$ and V matrices are the two components of the quasi-particle wave function.The expectation value of Eq. (1) in terms of density and pairing tensor can be expressed as an energy functional,

$$E[\rho, \kappa] = \frac{\langle \Phi | H | \Phi \rangle}{\langle \Phi | \Phi \rangle} = \mathrm{Tr}\left[\left(\hat{o} + \frac{1}{2}\Gamma\right)\rho\right] - \frac{1}{2}\mathrm{Tr}[\Delta \kappa^{*}] \quad (3)$$

where the HF self-consistent and the HFB pairing field termsterm is given by,

$$\tilde{A}_{k_1 k_2} = \sum_{k_2 k_4} \bar{o}_{k_1 k_2 k_3 k_4} \tilde{n}_{k_4 k_2} \;,\; \ddot{A}_{k_1 k_2} = \frac{1}{2} \sum_{k_3 k_4} \bar{o}_{k_1 k_2 k_3 k_4} \quad (4)$$

The variation of the energy (3) with respect to ρ and κ leads to the HFB equations:

$$\begin{pmatrix} \dot{o} + \tilde{A} - \ddot{e} & \ddot{A} \\ -\ddot{A}^{*} & -(\dot{o} + \tilde{A} - \ddot{e})^{*} \end{pmatrix} \begin{pmatrix} U \\ V \end{pmatrix} = E \begin{pmatrix} U \\ V \end{pmatrix} \quad (5)$$

Details about the energy density functional in terms of the Skyrme and Gogny two-body effective interactions can be obtained in refs [15, 16].

Results and Discussion

Then neutron skin thickness, neutron distribution, charge radii and proton and neutron radii of the even and even $^{124-208}$Sm (Z=62) isotopes have been investigated in the framework of the HFB method using the code HFBTHO (v3.00) [16]. The calculation have been performed within Skyrme type: SKI3 [17], HFB9 [18], UNE1 [19] and Gogny type:D1S [20, 21]forces.

The calculated charge radii (R_c) of the investigatedisotopeswith three different Skyrme type effective nucleon-nucleon interaction: Skyrme types SKI3, HFB9, UNE1 and Gogny force of typeD1S are shown in Fig.1 and compared with the RMF [22] and with the available experimental data [23]. The results are calculated from the proton radius by using the formula in units of fm, where R_p is the proton radii, R_c is the charge radii and 0.64 fm^2 term accounts the finite proton size. The calculated results show nice agreement with an available experimental measurements, especially in the region . The RMF calculations and the experimental one predict larger charge radii than do our HFB calculations.

The proton and neutron radii which obtained in our HFB calculations of Sm isotopes are shown in Fig.2. The calculations have been performed by applying Skyrme SKI3, HFB9, UNE1 and Gogny D1S force parameters. The D1S-Gogny force calculations [24] are indicated also for comparison. The proton and neutron radii plotted together to show the discrepancy between them. The R_p and R_n radii as seen from Fig. 2, start increase with neutron number increasing. The proton and neutron radii are almost the same near the valley of stability.

In Fig. 3, the neutron skin thickness: of even-even $^{124-208}$Sm (Z=62) isotopes plotted as a function of neutron number within D1S (purple line), SKI3 (red line), HFB9 (blue line), and UNE1 (green line) force parameters. The Neutrons layer is represented as the difference between rms of neutron and proton radii as mentioned in the formula. For nuclei near to the stability line this difference is found to be 1-2 fm.The theoretical calculations are estimated from the axially deformed solution of the Hartree-Fock-Bogoliubov equations using the harmonic oscillator basis model. The measurements of skin thickness are developing regularly with the neutron number increasing in the isotopes. This progressive development in the neutron skin may be related to the redistribution of the nucleons as a sequence of nuclear interactions with the addition of more neutrons holding the proton number fixed up to the neutron drip line.The predictions of HFB-Gogny [24] are taken for comparison. The D1S results give good agreements instead of other forces.The development of neutron skin thickness can be envisioned with the assistant of the density profile.

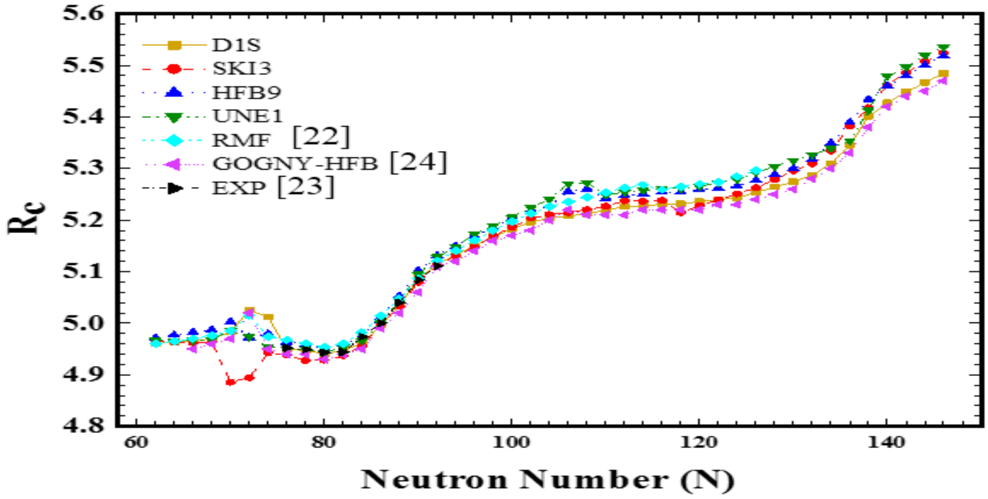

Fig. 1. Charge radii of the investigated Sm isotopes.

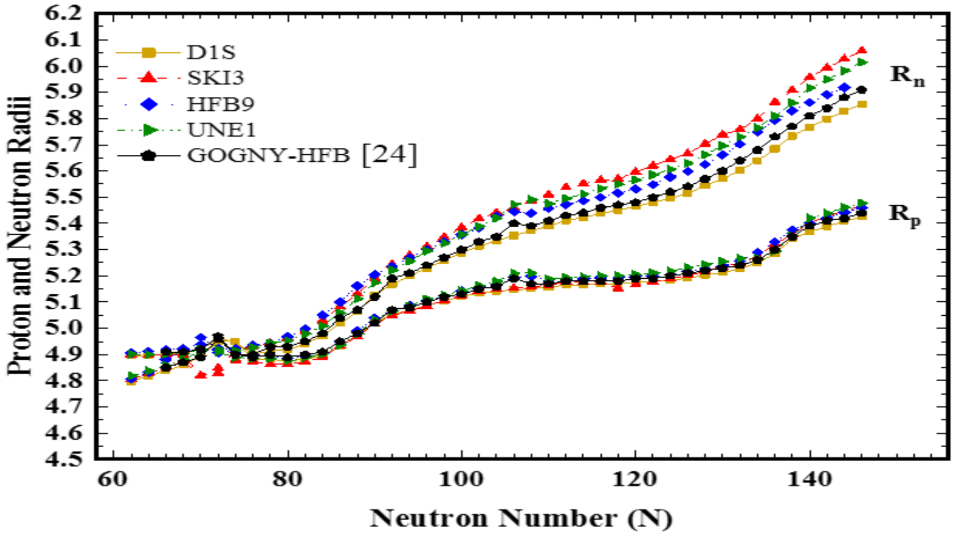

Fig. 2. Proton and neutron radii of the investigated Sm isotopes.

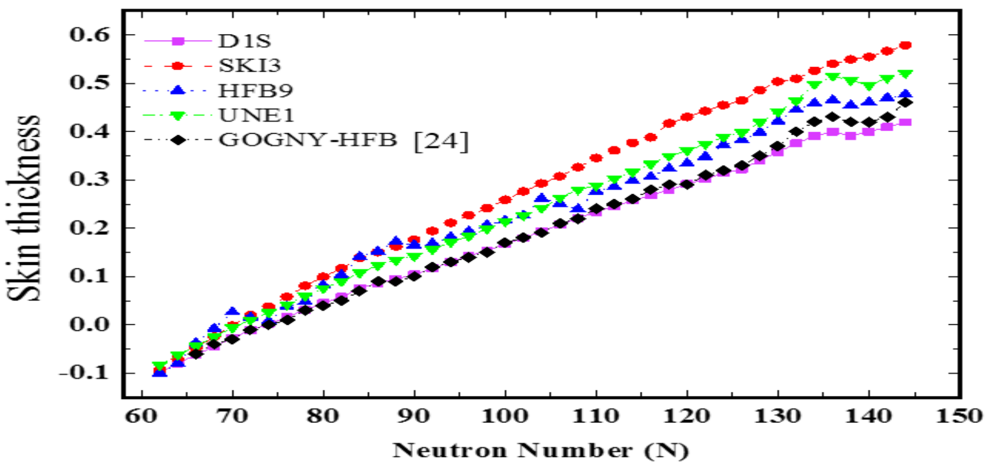

Fig. 3. Neutron skin thickness of the investigated Sm isotopes.

From Fig. 4, the neutron density distributions in even-even neutron-rich $^{142-158}$Sm isotopes have been performed within HFB method by using D1S, HFB9, SKI3, and UNE1 parameterizations. The neutron density results in Ref. [25] are also included for comparison. One obtains related features of the neutron density for all nuclei investigated in this study. A precise inspection of the neutron density gives a miniature difference at the central region for our forces for the chosen isotopes. This miniature difference may perform a significant role in the neutron pressure and effective nuclear symmetry energy coefficient. At r (fm) ≤ 2, all forces give a good agreement with available data [25], except D1S force which hasthe highest neutron density. After r (fm) = 2, all forces showed an increase in the density value with a peak is made, and these values begin to decrease at r (fm) ≥ 3 until it reaches zero. The theoretical density results are close to the experimental one especially for HFB9 force which is better than those D1S, SKI3, and UNE1 forces. Fig. 5, shows the neutron density distribution of $^{142-158}$Sm isotopes for the investigated interactions.

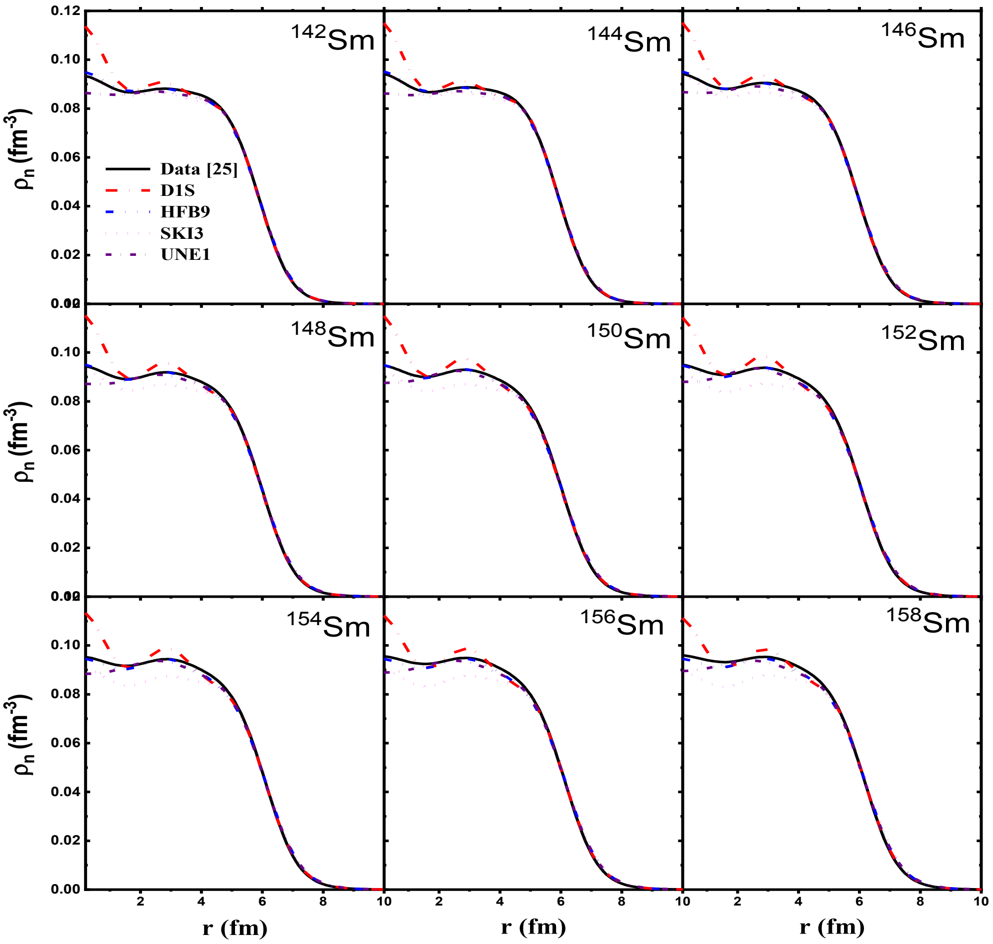

Fig. 4. Neutron density distribution of $^{142-158}$Sm isotopes obtained with HFB method.

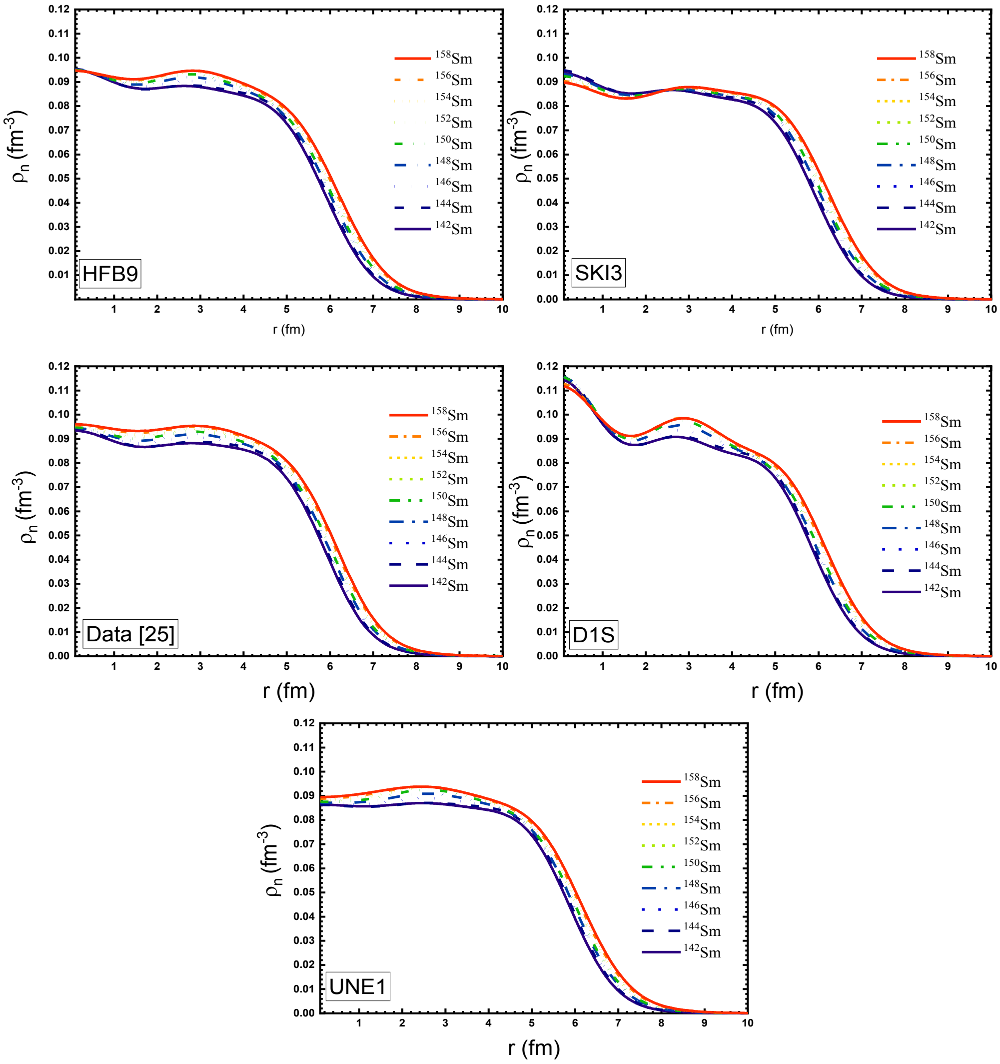

Fig. 5. Neutron density distribution of $^{142-158}$Sm isotopes for each interaction.

Conclusion

The neutron skin thickness, neutron distribution, charge, proton and neutron radiihave been calculated for $^{124-208}$Sm isotopes within the HFB method with three different Skyrme types effective nucleon-nucleon interaction: Skyrme types SKI3, HFB9, UNE1, and Gogny force of typeD1S. The theoretical charge radii of Sm isotopes for the parameter sets are approximately similar to the experimental data. The proton and neutron radii for D1S interaction give a good agreement in the comparison with HFB-Gogny predictions and also in the skin thickness, the D1S force gives a good agreement than other interactions. The theoretical neutron density results are close to the results of Ref. [25], especially for HFB9 force which is better than those D1S, SKI3, and UNE1 forces.

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سمك قشرة النيترون لنظائر $^{124-208}$Sm الزوجية-الزوجية

علي حسين تقي و صفاء مصطفى قتال
قسم الفيزياء-كلية العلوم-جامعة كركوك-كركوك-العراق.

كل الموجودات تتكون من ذرات تتوسطها النواة. لايزال فهم التركيب المعقد للنواة الذرية من التحديات الرئيسية، لذلك، فإن فيزياء النوى الغنية بالنيتورونات واحدة من اهم الموضوعات في فيزياء التركيب النووي من الناحية النظرية والتجريبية. تمتلك نظرية HFB (Hartree–Fock–Bogolyubov) إطارًا نظريًا جيدًا لوصف هذه النوى وذلك لأنها تعمم تقريب Hartree–Fock مع نظرية الاقتران BCS. في هذاالعمل، تم حساب سمك القشرة النيوتروني، توزيع النيوترونات، وأنصاف أقطار البروتون و النيوترون للنظائر الزوجية– الزوجية $^{124-208}$Sm (Z=62) في إطارحسابات HFB مع ثلاثة أنواع مختلفة من التفاعل الفعال االنيكلون–النيكلون Skyrmeللانواع: SKI3، HFB9، UNE1 و تفاعلGogny من النوع D1S. في ضوء الأنواع المختلفة الموجودة من النماذج والتفاعلات، يبقى السؤال أي منها يقدم أفضل وصف للبيانات. تمت مقارنة قيمنا المحسوبة معا لنتائج العملية والنظرية المتوفرة، حيث تم الحصول على توافقات جيدة.