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Structural analysis of Z=125 nuclei

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In this manuscript, we analyze the structural properties of neutron rich isotopes of Z = 125 super heavy nuclei in the mass range of $290 \leq A \leq 340$ within the framework of axially deformed relativistic mean field theory (RMF) and calculate the total binding energy, radii and quadrupole deformation parameter. Further, we extract one and two neutron separation energies for the considered isotopic chain. The density distribution has been also investigated for some fission survival nuclides, i.e., $^{310-320}125$ found in the studies of literature. We compare our results with the estimations made by finite range droplet model (FRDM) and a close agreement has been found.

Keywords: Neutron rich, Superheavy, Relativistic mean field theory, Binding energy, Separation energy

1 Introduction

The search for the limits on nuclear mass and charge in the valley of super heavy nuclei is still unexplored area of research in nuclear physics till now. The prediction of "Magic Island" or "Island of Stability"[1] has opened up new passage in study of super heavy nuclei (SHN). The existence of SHN is the result of the interplay of the attractive nuclear force and disruptive Coulomb force between protons that favours the fission. With the invention of the shell-correction method, it was established that SHN could exist due to the strong shell stabilization[2]. Taking this concept into consideration, a large number of SHN have been synthesized in the laboratory over the worldwide using hot and cold fusion reactions. Till now, Z = 118 has been observed and further attempts have also been made for higher Z values. In the line to extend the super heavy valley beyond Z=118, various theoretical calculations have been made. It is worth mentioning that the SHN are observed through alpha-decay. In literature[3], $^{310-320}125$ nuclides are suggested to be the candidate of fission survival and might be observed into the laboratory in future. Therefore, in order for the sake of completeness, we make an attempt of RMF calculations for these nuclei to look out the structural properties.

2 Theoretical Formalism

The starting point of the RMF theory is the basic lagrangian containing nucleons interacting with σ-, ω- and ρ-meson fields. The photon field A_μ is included to take care of the Coulomb interaction of protons. The relativistic mean-field lagrangian density[4] is expressed as:

$$\mathcal{L} = \bar{\psi}_i \{ i\gamma_\mu \partial_\mu - M \} \psi_i + \frac{1}{2}\left(\partial^\mu \sigma \partial_\mu \sigma - m_\sigma^2 \sigma^2\right) - \frac{1}{3} g^2 \sigma^3 - \frac{1}{4} g^3 \sigma^4 - g_s \bar{\psi}_i \psi_i \sigma - \frac{1}{4} \Omega^{\mu\nu} \Omega_{\mu\nu}$$

$$+ \frac{1}{2} m_\omega^2 V^\mu V_\mu - g_\omega \bar{\psi}_i \gamma^\mu \psi_i V_\mu + \frac{1}{2} c_4 \left(V^\mu V_\mu\right)^2 - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} + \frac{1}{2} m_\rho^2 R^\mu R_\mu - g_\rho \bar{\psi}_i i\gamma^\mu \tau \psi_i R^\mu$$

$$- \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - e\bar{\psi}_i i\gamma^\mu \frac{(1-\tau_{3i})}{2} \psi_i A_\mu$$

Here M, m_σ, m_ω and m_ρ are the masses for nucleon, σ-, ω- and ρ-mesons and ψ is the Dirac spinor. The field for the σ-meson is denoted by σ, ω-meson by V_μ and ρ-meson by R_μ. g_s, g_ω, g_ρ and $e^2/4\pi = 1/137$ are the coupling constants for the σ, ω, ρ-mesons and photon, respectively. g^2 and g^3 are the self-interaction coupling constants for σ-mesons. By using the classical variational principle, we obtain the field equations and a static solution is obtained from the equations of motion to describe the ground state properties of nuclei.

ρ_s and ρ_v are the scalar and vector density for σ- and ω-fields in nuclear system which are expressed as:

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$$\rho_s = \sum_{i=n,p} \bar{\psi}_i(r)\psi_i(r),$$

$$\rho_v = \sum_{i=n,p} \psi_i^\dagger(r)\psi_i(r).$$

The vector density $\rho_3(r)$ for ρ-field and charge density $\rho_c(r)$ are expressed by:

$$\rho_3 = \sum_{i=n,p} \psi_i^\dagger(r)\gamma^0\tau_{3i}\psi_i(r)$$

$$\rho_c = \sum_{i=n,p} \psi_i^\dagger(r)\gamma^0 \frac{(1-\tau_{3i})}{2}\psi_i(r)$$

The quadrupole deformation parameter β_2 is extracted from the calculated quadrupole moments of neutrons and protons through:

$$Q = Q_n + Q_p = \sqrt{\frac{16\pi}{5}}\left(\frac{3}{4\pi}AR^2\beta_2\right)$$

Where, R = 1.2 $A^{1/3}$

The various rms radii are defined as:

$$\langle r_p^2\rangle = \frac{1}{Z}\int r_p^2\, d^3r\rho_p$$

$$\langle r_n^2\rangle = \frac{1}{N}\int r_n^2\, d^3r\rho_n$$

$$\langle r_m^2\rangle = \frac{1}{A}\int r_m^2\, d^3r\rho$$

The total energy of the system is given by

$$E_{total} = E_{part} + E_\sigma + E_\omega + E_\rho + E_c + E_{pair} + E_{c.m.}$$

Where, E_{part} is the sum of the single-particle energies of the nucleons and E_σ, E_ω, E_ρ, E_c, E_{pair}, $E_{c.m.}$ are the contributions of the meson fields, the Coulomb field, pairing energy and the center of mass energy, respectively. In present calculations, we use the constant gap BCS approximation to take care of pairing interaction[5]. Third generation of non-linear[6] NL3 parameter set is used throughout the calculations.

3 Results and Discussion

We employ axially deformed self-consistent relativistic mean-field model within NL3 effective force and calculate the binding energy, radii and quadrupole deformation. As we have mentioned earlier, in literature[3], Z = 125 nuclei with A = 310-320 are suggested to be alpha-decay active isotopes. Therefore, in order for the completeness, we make detailed structural calculations for these nuclides and the results are presented in forth subsections.

3.1 Binding energy, radii and quadrupole deformation parameter

A static solution is obtained from the equations of motion to describe the ground state properties of nuclei. To find the possible ground state configuration of these nuclides, the calculations are performed with an initial prolate quadrupole deformation parameter β_0. Total binding energy and quadrupole deformation parameter for the considered isotopic chain $^{290-340}125$ have been plotted in Fig. 1.

As the experimental binding energies for these super heavy isotopic chains are not available, so in order to provide some validity to the predictive power of our calculations a comparison of binding energies of our calculations with those obtained from finite range droplet model (FRDM)[7] is made wherever available and close agreement is found. It is evident from Fig. 1, binding energy monotonically increases with increasing neutron number. Initial few isotopes shows slightly prolate structure upto A = 295 then spherical till A = 308 and again prolate shapes. The values of deformation parameter obtained from FRDM predict the ground state of most of the nuclei in the considered isotopic chain to be spherical and prolate. In contrary with our RMF calculations it predicts few oblate nuclei too. We have also calculated the rms radii and plotted in Fig. 2. The radii monotonically increases with increasing the mass number. A sudden change in radii at A = 315 (N=190) clues a large change in structure configuration and a possible superdeformed superheavy nuclei are suggested.

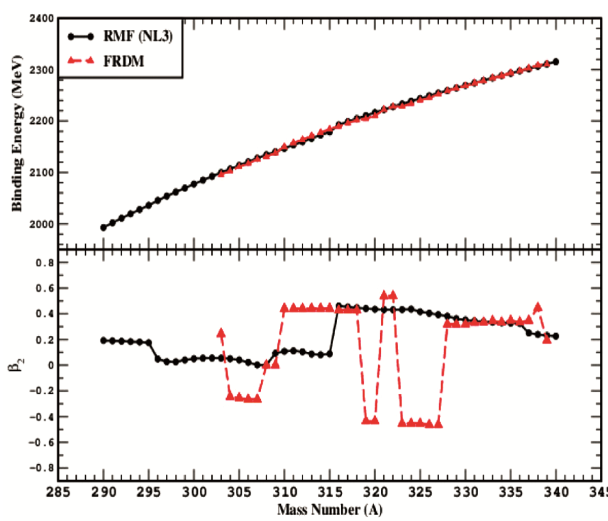

Fig. 1 – Binding energy (top) and quadrupole deformation parameter (bottom) as function of mass number.

3.2 Separation energy

The separation energy is an important observable in identifying the signature of magic numbers in nuclei. The magic numbers in nuclei are characterized by large shell gaps in their single-particle energy levels. This implies that the nucleons occupying the lower energy level have comparatively large value of energy than those nucleons occupying the higher energy levels, difference of their energies shows a kink on separation energy plot. We have extracted one-neutron and two-neutron separation energies (S_{1n} and S_{2n}) and plotted in Fig. 3. The S_{1n} and S_{2n} are given by:

$$S_{1n} = BE(Z,N) - BE(Z,N-1)$$
$$S_{2n} = BE(Z,N) - BE(Z,N-2)$$

Separation energies calculated using finite range droplet model (FRDM) has also been plotted here and they are in good agreement with that found using RMF calculation. No kink is observed over the whole considered issotopic chain shown in Fig. 3. It implies that no magic behaviour is revealed in the nuclides of Z = 125. Further, for more understanding, nuclon distributions have been examined using the density profile.

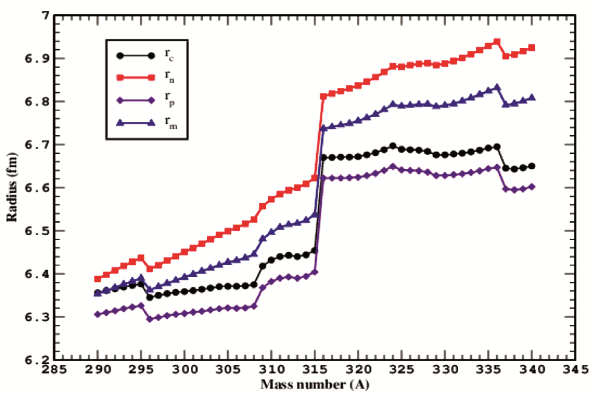

Fig. 2 – Radii as a function of mass number.

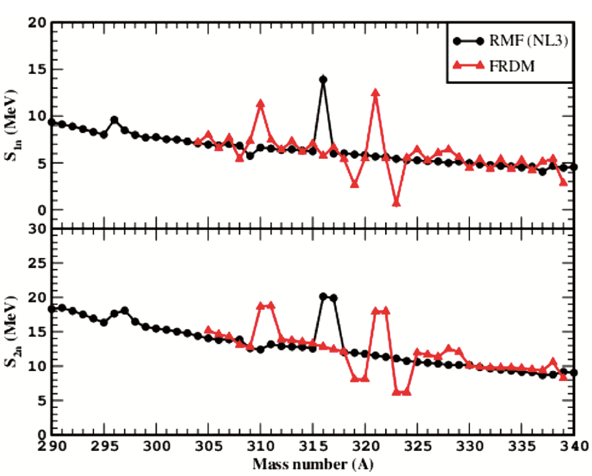

Fig. 3 – One and two neutron separation energies as a function of mass number.

3.3 Density distribution

Density distribution provides detailed information regarding the distribution of nucleons for identifying bubble, halo and cluster structures of the nuclei that may be observed in light to super heavy nuclei[8]. Density profile of nucleons has been plotted for alpha-decay active nuclides[3], (i.e., $^{310\text{-}320}125$) is shown in Fig. 4. Here, depletion of central density is observed for $^{310\text{-}315}125$ and these nuclei are suggested to be the bubble nuclei. However, special and different kinds of proton distribution are noticed for these nuclides and therefore, contour or 3D plot is necessary in order for more clear presentation of nucleon distribution. The strength of bubble shape is evaluated by calculating the depletion fraction[9].

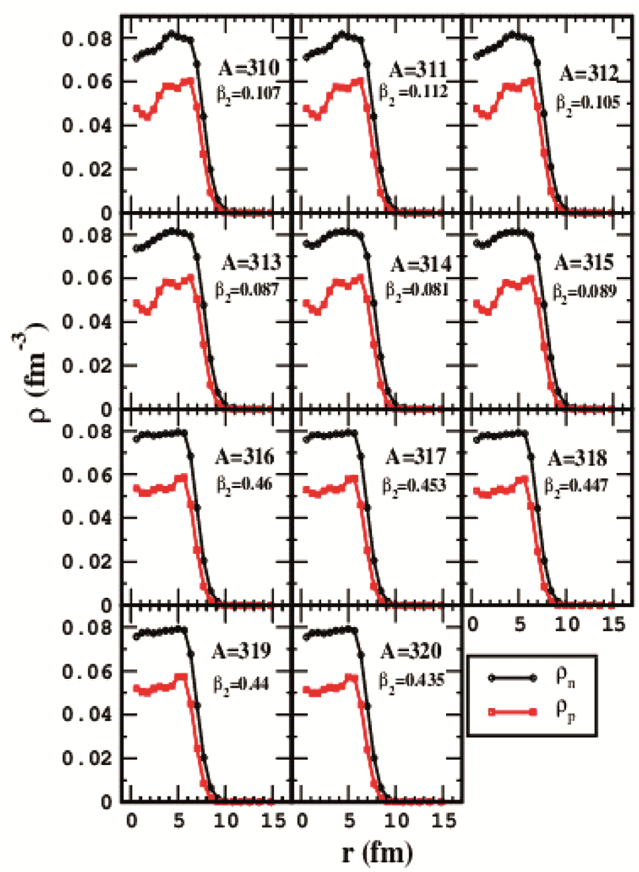

Fig. 4 – Neutron and proton density distribution as a function of radial parameter.

4 Conclusions

We have calculated the structural properties of Z = 125 super heavy nuclei with a mass range of A = 290 - 340 within axially deformed relativistic mean-field theory. The calculations are performed for prolate configuration as most of the neutron rich super heavy nuclei have prolate structure in ground state. The results produced by RMF are in good agreement with FRDM data. Density distribution has been examined to explain the special features of the nuclei such as bubble or halo structure. Bubble structure is seen for some of the isotopes of nuclei under investigation.

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References

1 Cwiok S C, Dobaczewski J, Heenen P H, Magierski P, & Nazarewicz W, *Nucl Phys A*, 611 (1996) 211.
2 Myers W D, Swiatecki W J, *Nucl Phys A*, 81 (1966) 1.
3 Santhosh K P & Nithya C, *Phys Rev C*, 97 (2018) 044615.
4 Gambhir Y K, Ring P & Thimet A, *Ann Phys (N Y)*, 198 (1990) 132.
5 Serot B D, *Rep Prog Phys*, 55 (1992) 1855.
6 Lalazissis G A, Konig J & Ring P, *Phys Rev C*, 55 (1997) 540.
7 Möller P, Sierk A J, Ichikawa T, & Sagawa H, *At Data Nucl Data Tables*, 109 (2016) 1.
8 Wilson H A , *Phys Rev C*, 69 (1946) 538.
9 Madland D G & Nix R J, *Nucl Phys A*, 476 (1988) 1.