The $\alpha$- decay chains of the $^{287,288}\text{115}$ isotopes using relativistic mean field theory

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We study the binding energy, root-mean-square radius, and quadrupole deformation parameter for the synthesized superheavy element (SHE) $Z = 115$, within the formalism of relativistic mean field theory (RMF). The calculation is done for various isotopes of $Z = 115$ element, starting from $A = 272$ to $A = 292$. A systematic comparison between the binding energies and experimental data is made. The calculated binding energies are in good agreement with experimental result. The results show the prolate deformation for the ground state of these nuclei. The most stable isotope is found to be $^{282}\text{115}$ nucleus ($N = 167$) in the isotopic chain. We have also studied $Q_{\alpha}$ and $T_{\alpha}$ for the $\alpha$- decay chains of $^{287,288}\text{115}$.

1. Introduction

Studies aimed at the identification of new superheavy elements which contribute to the fundamental knowledge of nuclear potentials and the resulting nuclear structure. The concept of an “Island of stability” existing near the next spherical doubly magic nucleus heavier than $^{208}\text{Pb}$ arises in every advanced model of nuclear structure. The elements up to $Z = 118$ have been synthesized till today with half-lives varying...
from a few minutes to milliseconds. But theoretically predicted center of the island of stability could not be located. More microscopic theoretical calculations have predicted various regions of stability, namely \( Z = 120, \ N = 172 \) or \( 184 \) and \( Z = 124 \) or \( 126, \ N = 184 \)\(^{[7,8]}\). There is a need to design the new experiments to solve the outstanding problem of locating the precise island of stability for superheavy elements. Measurements on the \( \alpha \)-decays provide reliable information on nuclear structure such as ground state energies, half-lives, nuclear spins and parities, shell effects, nuclear deformation and shape co-existence\(^{[9,10,11,12,13,14,15,16,17]}\). Therefore as one of the most important decay channels for unstable nuclei, \( \alpha \)-decay is extensively investigated both experimentally and theoretically.

Both non-relativistic (e.g. Skyrme Hartree Fock) theory\(^{[18,19]}\) and relativistic microscopic mean field formalism (RMF)\(^{[20,21]}\) predict probable shell closures at \( Z = 114 \) and 120. Microscopic interaction for the existence of the heaviest element was estimated by Meitner and Frisch\(^{[22]}\). Myers and Swiatecki\(^{[23]}\) estimated the fission barriers for wide range of nuclei and also far into the unknown region of superheavy elements. The historical review on theoretical predictions and new experimental possibilities are given by A. Sobiczewski, F. A. Garrev and B. N. Kalinkin\(^{[24]}\). A considerable increase in nuclear stability was expected for the heaviest nuclei with \( N > 170 \) in the vicinity of the closed spherical shells, \( Z = 114 \) (or possibly 120, 122 or 126) and \( N = 184 \), similar to the effect of the closed shells on the stability of the doubly magic \( ^{208}\)Pb (\( Z = 82, \ N = 126 \))\(^{[3,4,5]}\). The change of shape from spherical to deformed (oblate/prolate) configuration in the \( \alpha \)-decay process gives us valuable information about the nuclear structure properties\(^{[25,26,27,28,29]}\). The fusion-evaporation reaction of \( ^{243}\)Am + \( ^{48}\)Ca, leads to the formation of \( ^{291}{\text{115}} \) nuclei. According to the predictions\(^{[25,26]}\), the 3n- and 4n- evaporation channels results the odd-odd isotope \( ^{288}\)115 (\( N = 173 \)) and odd-A isotope \( ^{287}\)115 (\( N = 172 \)). Here our basic motivation is to study the \( \alpha \)-decay properties of these synthesized isotopes. It is also worth mentioning that the scientists at Dubna re-performed the same experiment, where the results are yet to be published\(^{[30]}\).

The relativistic mean field (RMF) formalism is presented in section II. The results of our calculation are in section III. Section IV includes the \( \alpha \)-decay modes of \( ^{288}\)115 and \( ^{287}\)115 isotopes. Summary of our results is given in section V.

2. The relativistic mean-field (RMF) formalism

The microscopic self consistent calculation is now a standard tool to investigate the nuclear structure. The starting point of the RMF theory is the basic Lagrangian\(^{[31]}\) (The Linear Walecka Model) that describes nucleons as Dirac spinors interacting with the meson fields. However, the original Lagrangian of Walecka has taken several modifications to take care of various limitations and the recent successful relativistic Lagrangian density for a nucleon-meson many body system\(^{[20,21]}\) is expressed as,
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\[
\mathcal{L} = \bar{\psi} \{ i \gamma^\mu \partial_\mu - M \} \psi + \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 \\
- \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4 - g_s \bar{\psi} \gamma_5 \psi \sigma - \frac{1}{4} \Omega^{\mu\nu} \Omega_{\mu\nu} \\
+ \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu + \frac{1}{4} c_3 (\omega^\mu \omega_\mu)^2 - g_w \bar{\psi} \gamma_5 \omega^\mu \psi \omega_\mu \\
- \frac{1}{4} \bar{B}^{\mu\nu} B_{\mu\nu} + \frac{1}{2} m_\rho^2 \bar{R}^\mu R_\mu - g_\rho \bar{\psi} \gamma_5 \rho^\mu \psi \rho_\mu \\
- \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - g \bar{\psi} \gamma_5 \frac{1 - \tau_3}{2} \psi A_\mu.
\]

Where $m$ is the bare nucleon mass and $\psi$ is its Dirac spinor. Nucleons interact with the $\sigma$, $\omega$, and $\rho$ mesons. We obtain the field equations for the nucleon and mesons. The self-consistent iteration method solved the coupled equations. The c.m. (center of mass) motion energy correction is estimated by the harmonic oscillator formula $E_{c.m.} = \frac{3}{4} (41A^{-1/3})$. From the resulting proton and neutron quadrupole moments, the quadrupole deformation parameter $\beta_2$, as $Q = Q_n + Q_p = \sqrt{\frac{16\pi}{3} \frac{3}{4\pi} AR^2 \beta_2}$. The root mean square (rms) matter radius is defined as $\langle r_m^2 \rangle = \frac{3}{4\pi} \int \rho(r,z) r^2 d\tau$, where $A$ is the mass number, and $\rho(r,z)$ is the deformed density. The total binding energy and other observables are also obtained by using the standard relations, given in [21]. We use the well known NL3 parameter set [32]. This set reproduces the properties of the stable nuclei and also predicts for those far from the $\beta$-stability valley. We obtain different potentials, densities, single-particle energy levels, radii, deformations and the binding energies. The maximum binding energy corresponds to the ground state for a given nucleus and other solutions (intrinsically excited state) are also obtained.

3. Results and Discussion

Here we investigated the bulk properties like the binding energies (BE), quadrupole deformation parameters $\beta_2$, charge radii ($r_{ch}$), pairing energies $E_{pair}$ by using the relativistic Lagrangian with the successful NL3 force parameter. Earlier, it is reported that most of the recent parameter sets reproduce well the ground state properties, not only for stable normal nuclei but also for exotic nuclei far away from the $\beta$-stability [21, 32, 33, 34, 35].

3.1. Binding energy and two-neutron separation energy

The total binding energy (BE) for whole isotopic chain for $Z = 115$ is plotted in Fig. 1(a) and also listed in Table I. From Fig. 1(a) and Table I, we notice that the microscopic RMF (NL3) BE over estimated than that of FRDM at $N = 156 - 167$, after that the difference in binding energy decreasing towards the higher mass region (around $A=287$). And beyond to this mass number the two curves again showing a similar behaviour.
Table 1. The RMF (NL3) results for binding energy BE, two-neutron separation energy $S_{2n}$, pairing energy $E_{pair}$, the binding energy difference $\Delta E$ between the ground- and first-excited state solutions, and the quadrupole deformation parameter $\beta_2$, compared with the corresponding Finite Range Droplet Model (FRDM) results. The energy is in MeV.

| Nucleus | RMF (NL3) Result | FRDM Result |
|---------|------------------|-------------|
|         | BE   | $S_{2n}$ | $E_{pair}$ | $\Delta E$ | $\beta_2$ | BE   | $S_{2n}$ | $\beta_2$ |
| 272     | 1944.3 | 16.7    | 17.3      | 6.51      | 0.255    | 1932.8 | 16.7      | 0.182    |
| 274     | 1961.0 | 16.6    | 16.9      | 6.20      | 0.244    | 1950.3 | 17.5      | 0.192    |
| 276     | 1977.2 | 16.3    | 16.3      | 5.87      | 0.232    | 1967.4 | 17.1      | 0.202    |
| 278     | 1992.8 | 15.6    | 15.8      | 5.30      | 0.218    | 1983.9 | 16.5      | 0.202    |
| 280     | 2008.0 | 15.1    | 15.4      | 4.77      | 0.196    | 2000.3 | 16.4      | 0.053    |
| 282     | 2022.8 | 14.7    | 14.7      | 4.15      | 0.182    | 2015.8 | 15.5      | 0.053    |
| 284     | 2036.7 | 13.9    | 14.3      | 3.18      | 0.173    | 2030.8 | 15.0      | 0.062    |
| 286     | 2049.8 | 13.1    | 14.0      | 2.06      | 0.165    | 2045.2 | 14.4      | 0.071    |
| 288     | 2062.5 | 12.7    | 13.7      | 1.23      | 0.152    | 2059.1 | 13.8      | -0.087   |
| 290     | 2074.5 | 11.9    | 13.6      | 0.15      | 0.103    | 2072.6 | 13.5      | -0.079   |
| 292     | 2086.5 | 11.9    | 13.5      | 0.02      | 0.060    | 2085.7 | 13.1      | -0.061   |

Fig. 1. (a) The binding energy BE for the $^{272-292}$115 isotopes, obtained in RMF (NL3) formalism are compared with the FRDM results. (b) Same as Fig. 1(a) but for binding energy per particle BE/A.

The binding energy per nucleon ($BE/A$) for the isotopic chain is plotted in Fig. 1(b). The BE/A value starts reaching a peak value at $A = 282$ for RMF (NL3) and at $A = 286$ for FRDM. It means $^{282}$115 is the most stable isotope from the RMF (NL3) and $^{286}$115 from the FRDM results. From the above, it is
clear that FRDM predicted $N = 171$ closed to predicted closed shell $N = 172$, which is not appear in case of RMF (NL3).

![Graph showing two neutron separation energy and pairing energy]

Fig. 2. The two-neutron separation energy $S_{2n}$ for $^{272-292}115$ nuclei, obtained from RMF (NL3) formalisms, and compared with the FRDM results, wherever available. (b) The pairing energy $E_{pair}$, for the relativistic RMF (NL3) formalism.

The two neutron separation energy $S_{2n} (N, Z) = BE (N, Z) - BE (N-2, Z)$ is mentioned in Table I. The comparisons of $S_{2n}$ for the RMF and FRDM models are shown in Fig. 2(a), which shows that the two $S_{2n}$ values coincide remarkably well. $S_{2n}$ values decrease gradually with increase of the neutron number, except for the noticeable kinks at $A = 282 (N=167)$ in RMF and there is no such behaviour in FRDM.

Pairing is important for open shell nuclei whose value, for a given nucleus, depends only marginally on quadrupole deformation parameter $\beta_2$. $E_{pair}$ is shown in Fig. 2(b) for the RMF (NL3) calculation. It is clear from Fig. 2(b) that $E_{pair}$ decreases with increase in mass number $A$, i.e., even if the $\beta_2$ values for two nuclei are the same, the $E_{pairs}$ are different from one another. While comparing the results of paring energy obtained from semi-empirical-mass formula with empirical value of the average pairing gap $\Delta \sim 12.A^{-1/2}$, the pairing energy $E_{pairs}$ from RMF (NL3) calculations overestimated than that of the empirical values, saying the failure of extrapolation to SHE region of the phenomenological formula.

### 3.2. Quadrupole deformation parameter

The quadrupole deformation parameter $\beta_2$, for both the ground and first excited states, are also determined within the RMF formalism. In some of the ear-
lier RMF calculations, it was shown that the quadrupole moment obtained from these theories reproduce the experimental ground state (g.s.) data pretty well. The g.s. quadrupole deformation parameter $\beta_2$ is plotted in Fig. 3(a) for RMF, and compared with the FRDM results. It is clear from this figure that the FRDM results differ from the RMF (NL3) results for some mass regions. For example, the prolate structure has been found for all the isotopes within RMF. There is a shape change from prolate to oblate at $A = 286$ ($N = 171$) to $A = 288$ ($N = 173$) in FRDM.

![Fig. 3. (a) Quadrupole deformation parameter obtained from relativistic mean field formalism RMF (NL3), compared with the FRDM results, where ever available. (b) The energy difference between the ground-state and the first excited state $\Delta E$ compared with the FRDM results.](image)

### 3.3. Shape co-existence

The binding energy difference $\Delta E$ is the energy difference between the ground state (g.s.) and the first excited state (e.s.). $\Delta E$ is plotted in Fig. 3(b). From Fig. 3(b), we notice that $\Delta E$ decreases with increase in mass number $A$ in the isotopic series. There is a small difference in binding energy with increase in neutron number. It is an indication of shape co-existence. For example, in $^{280}_{115}$ the two solutions for $\beta_2 = 0.103$ and $\beta_2 = -0.176$ are completely degenerate with binding energies of 2074.53 and 2074.38 MeV. This result shows that the g.s. can be changed to the e.s. and vice-versa, by a small change in the input like the pairing strength etc. in the calculations. Such a phenomenon exists in many other regions of the periodic table.
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3.4. **Nuclear radii**

The root-mean-square matter radius ($r_m$) and charge radius ($r_{ch}$) for the RMF (NL3) formalism are shown in Fig. 4. It clearly shows that the rms radius increases with increase of the neutron number. Though the proton number $Z = 115$ is constant for the isotopic series, the $r_{ch}$ value also increases with neutron number. Both the radii jump to a lower value at $A = 282$ (with $N = 167$).

A detailed inspection of Fig. 4 shows that, in the RMF calculations, both the radii show the monotonic increase of radii till $A = 293$, with a jump to a lower value at $A = 290$ (with $N = 175$). There is no data or other calculation available for comparisons.

4. The $Q_\alpha$ energy and the decay half-life $T_{1/2}^\alpha$

The $Q_\alpha$ energy is obtained from the relation:\[Q_\alpha(N, Z) = BE(N, Z) - BE(N - 2, Z - 2) - BE(2, 2).\] Here, $BE(N, Z)$ is the binding energy of the parent nucleus with neutron number $N$ and proton number $Z$, $BE(2, 2)$ is the binding energy of the $\alpha$-particle ($^4\text{He}$), i.e., 28.296 MeV, and $BE(N - 2, Z - 2)$ is the binding energy of the daughter nucleus after the emission of an $\alpha$-particle.

With the $Q_\alpha$ energy at hand, we estimate the half-life time $T_{1/2}^\alpha$ by using the phenomenological formula of:\[\log_{10} T_{1/2}^{ph}(Z, N) = aZ[Q_\alpha(Z, N) - E_i]^{-1/2} + bZ + c.\] with $Z$ as the atomic number of the parent nucleus. Where the parameters $a =$
Table 2. The $Q_\alpha$ energy and half-life $T_{1/2}^\alpha$ for $\alpha$-decay series of $^{287}_{115}$ nucleus, calculated on the RMF (NL3) model, and compared with the Finite Range Droplet Model (FRDM) results, the results of other authors, and the experimental data, wherever available. The experimental $Q_\alpha$ value is calculated from the given kinetic energy of $\alpha$-particle. The energy is in Mev.

| A  | Z  | Ref. | BE    | $Q_\alpha$ | $T_{1/2}^\alpha$ |
|----|----|------|-------|------------|------------------|
| 287| 115| Expt.25,26 | 10.74 | 32$^{+155}_{-14}$ ms |
|    |    | RMF   | 2056.3 | 11.304 | 0.0158 s |
|    |    | FRDM  | 2052.7 | 10.256 | 4.265 s |
|    |    |       | 10.789 | 0.155 s |
|    |    |       | 11.21  | 3.55 ms |
| 283| 113| Expt.25,26 | 10.26 | 100$^{+490}_{-45}$ ms |
|    |    | RMF   | 2039.3 | 10.081 | 5.807 s |
|    |    | FRDM  | 2034.6 | 9.346  | 426.57 s |
|    |    |       | 10.313 | 0.676 s |
|    |    |       | 11.12  | 1.39 ms |
| 279| 111| Expt.25,26 | 10.52 | 170$^{+810}_{-80}$ s |
|    |    | RMF   | 2021.1 | 9.6    | 26.721 s |
|    |    | FRDM  | 2015.3 | 10.93  | 4.365 s |
|    |    |       | 10.57  | 0.034 s |
|    |    |       | 11.08  | 0.417 ms |
| 275| 101| Expt.25,26 | 10.48 | 9.7$^{+4.6}_{-4.6}$ ms |
|    |    | RMF   | 2002.4 | 9.47   | 15.522 s |
|    |    | FRDM  | 1998.3 | 10.07  | 0.170 s |
|    |    |       | 10.53  | 0.010 s |
|    |    |       | 10.34  | 6.36 ms |
| 271| 107| Expt.25,26 | -     | -      | - |
|    |    | RMF   | 1983.6 | 9.58   | 1.47 s |
|    |    | FRDM  | 1980.1 | 8.66   | 575.43s |

1.5372, $b = -0.1607$, $c = -36.573$ and the parameter $\overline{E}_i$ (average excitation energy of the daughter nucleus) is,

$$\overline{E}_i = \begin{cases} 
0 & \text{for } Z \text{ even } - N \text{ even} \\
0.113 & \text{for } Z \text{ odd } - N \text{ even} \\
0.171 & \text{for } Z \text{ even } - N \text{ odd} \\
0.284 & \text{for } Z \text{ odd } - N \text{ odd}.
\end{cases}$$

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Fig. 5. (a) The $Q_\alpha$-energy for $\alpha$-decay series of $^{287,115}$ nucleus, using the relativistic mean field formalism RMF (NL3), compared with the FRDM data, the results of Silisteanu et al., Samanta et al. and the experimental data, wherever available. (b) The half-life time $T_\alpha$ for $^{287,115}$ nucleus using the RMF(NL3), FRDM, the results of Silisteanu et al. and Samanta et al.

Fig. 6. Same as Fig. 5, but for $^{288,115}$ nuclear chain.
Table 3. Same as Table II, but for $^{288}115$ nuclear chain.

| A  | Z  | Ref.   | BE    | $Q_\alpha$ | $T_{1/2}^{\alpha}$ |
|----|----|--------|-------|------------|-------------------|
| 288| 115| Expt. 25, 26 |       | 10.61      | $87^{+105}_{-30}$ ms |
|    |    | RMF    | 2063.0| 10.81      | 0.288 s           |
|    |    | FRDM 36, 37 | 2059.1| 10.13      | 21.37 s           |
|    |    | 47     | 10.68 | 0.668 s    |                   |
|    |    | 48     | 10.95 | 0.056 s    |                   |
| 284| 113| Expt. 25, 26 |       | 10.15      | $4.8^{+0.58}_{-0.17}$ s |
|    |    | RMF    | 2045.5| 9.93       | 15.416 s          |
|    |    | FRDM 36, 37 | 2041.0| 9.16       | 4073.802 s        |
|    |    | 47     | 10.19 | 3.206 s    |                   |
|    |    | 48     | 10.68 | 0.0605 s   |                   |
| 280| 111| Expt. 25, 26 |       | 9.87       | $3.6^{+4.3}_{-1.3}$ s |
|    |    | RMF    | 2027.1| 9.40       | 123.104 s         |
|    |    | FRDM 36, 37 | 2021.8| 10.13      | 1.0715 s          |
|    |    | 47     | 9.94  | 3.68 s     |                   |
|    |    | 48     | 10.77 | 0.0082 s   |                   |
| 276| 109| Expt. 25, 26 |       | 9.85       | $0.72^{+0.87}_{-0.25}$ s |
|    |    | RMF    | 2008.2| 9.13       | 180.267 s         |
|    |    | FRDM 36, 37 | 2003.6| 9.93       | 0.89 s            |
|    |    | 47     | 9.90  | 1.061 s    |                   |
|    |    | 48     | 10.09 | 0.101 s    |                   |
| 272| 107| Expt. 25, 26 |       | 9.15       | $9.8^{+11.7}_{-5.5}$ s |
|    |    | RMF    | 1989.0| 9.36       | 6.74 s            |
|    |    | FRDM 36, 37 | 1985.3| 8.89       | 229.086 s         |
|    |    | 47     | -     | 24.1 s     |                   |
|    |    | 48     | 9.08  | 16.5 s     |                   |

4.1. The $\alpha$-decay series of $^{287}115$ nucleus

We evaluate the BE by using RMF formalism and from these, we estimated the $Q_\alpha$ for whole isotopic chain. We have calculated half-life time $log_{10}T_\alpha$ by using the above formulae. Our predicted results by using RMF model are compared in Table III with the Finite range droplet model (FRDM) calculation 36,37, the results from Silisteanu et al. 47, Samanta et al. 48, and experimental data 25,26 wherever possible. The comparison of $Q_\alpha$ and $log_{10}T_\alpha$(s) are shown in Fig.5(a) and 5(b). From Figure, we notice that the calculated values of both $Q_\alpha$ and $T_\alpha$ agree well with the result of Silisteanu et al., Samanta et al. and experimental data.
4.2. The α-decay series of $^{288}$115 nucleus

From the BE, which have calculated from RMF formalism, we evaluated $Q_{\alpha}$ and $log_{10}T_{\alpha}(s)$ for whole isotopic chain. The predicted results are compared with FRDM predictions, Sillageau et al., Samanta et al., experimental data, wherever possible. From Fig. 6(a), 6(b) and Table II, we found that RMF results agree well with the results of Sillageau et al. and Samanta et al. and the experimental data.

5. Summary

We have calculated the binding energy, rms charge and matter radii, quadrupole deformation parameter of the isotope of $^{287}$115 and $^{288}$115 and also investigated two-neutrons separation energy and energy difference between ground and first excited state, for studying the shape co-existence, pairing energy, for the isotopic chain of $Z = 115$. We observed the most stable isotope is $^{282}$115. The value of $Q_{\alpha}$ and $T_{\alpha}$ are in good agreement with the available experimental data. We have seen that the RMF theory provides a reasonably good description for whole isotopic chain.

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