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Superheavy elements and decay properties

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Abstract. The α decay properties of the isotopes of $Z = 115$, 117, 118 and 119 have been extensively investigated, focussing on the newly synthesized isotopes within the Coulomb and proximity potential model for deformed nuclei (CPPMDN). The α half-lives have also been evaluated using the Viola–Seaborg systematic (VSS) and the analytical formulae of Royer and it can be seen that our calculated values match well with these theoretical values. The mode of decay of these isotopes has also been studied by calculating the spontaneous fission half-lives. Thus, we have predicted 4α chains from $^{287}115$, 3α chains from $^{288}115$, 3α chains from $^{293}117$, 4α chains from $^{294}117$ and 3α chains from $^{294}118$ and, it can be seen that our predictions on the α decay chains also match well with the experimental observations. The study on $Z = 119$ has predicted six consistent α chains from $^{292-295}119$, 5α chains from $^{296}119$, 4α chains from $^{297}119$ and 3α chains from $^{298,299}119$. Thus, through our study on isotopes of $Z = 115$, 117, 118 and 119 superheavy nuclei, we could predict the range of isotopes that may be detectable using α decay and we hope that the findings on the isotopes of $Z = 119$ will provide a new guide for future experiments.

Keywords. Alpha decay; spontaneous fission; superheavy nuclei.

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1. Introduction

The synthesis and identification of new isotopes in the superheavy (SH) region has always been a fascinating field of research to nuclear physicists. The tremendous progress achieved in the heavy-ion beam technologies and accelerator facilities has hastened the production of new isotopes in the SH region. The cold fusion reactions [1,2] and the hot fusion reactions [3] are the two methods employed by experimentalists in synthesizing the superheavy nuclei (SHN). The experimental studies being performed in the SH region aim at drawing theoretical attention to understand the nuclear structure of these nuclei and thus obtain information about the so-called magic island or island of stability beyond $Z = 82$, $N = 126$ and around $Z = 120$, 124 or 126 and $N = 184$ [4]. Extensive theoretical studies [5–14] have been carried out by various theoretical groups on various microscopic properties of SHN and valuable information on nuclear binding energies, nuclear structure and nuclear decay mechanisms have been obtained from the decay half-life determinations. SHN usually undergo spontaneous decay into successive α decay chains, which lead to known isotopes before spontaneous fission.

We have performed several theoretical studies [15–26] on both heavy particle decay and α decay of heavy and superheavy nuclei within the Coulomb and proximity potential model (CPPM) [25,26] and the Coulomb and proximity potential model for deformed nuclei (CPPMDN) [15]. Even though theoretical studies on isotopes having $Z = 115$ [18], $Z = 117$ [19,20], $Z = 118$ [21] and $Z = 119$ [22] have already been performed by us, in this study focus is given to the recently synthesized SHN $^{287,288}115$, $^{293,294}117$ and $^{294}118$.

2. The Coulomb and proximity potential model for deformed nuclei (CPPMDN)

In Coulomb and proximity potential model for deformed nuclei (CPPMDN), the potential energy barrier is taken as the sum of the deformed Coulomb potential, deformed two-term proximity potential and centrifugal potential for both the touching configuration and separated fragments. The simple power-law interpolation done by Shi and Swiatecki [27] is used for the pre-scission (overlap) region. The interacting potential for two spherical nuclei is given by

$$V = \frac{Z_1 Z_2 e^2}{r} + V_{\mathrm{P}}(z) + \frac{\hbar^2 \ell(\ell+1)}{2\mu r^2}, \quad \text{for } z > 0. \tag{1}$$

Here Z_1 and Z_2 are the atomic numbers of the daughter and the emitted cluster, z is the distance between the near surfaces of the fragments, r is the distance between fragment centres and is given as $r = z + C_1 + C_2$, where C_1 and C_2 are the Süsmann central radii of fragments. The term ℓ represents the angular momentum, μ is the reduced mass and V_{P} is the proximity potential. The proximity potential V_{P} is given by Blocki *et al* [28,29] as

$$V_{\mathrm{P}}(z) = 4\pi\gamma b \left[\frac{C_1 C_2}{C_1 + C_2}\right] \Phi\left(\frac{z}{b}\right) \tag{2}$$

with the nuclear surface tension coefficient,

$$\gamma = 0.9517[1 - 1.7826(N-Z)^2/A^2]\ \mathrm{MeV/fm^2}, \tag{3}$$

where N, Z and A represent neutron number, proton number and mass number of parent, Φ represents the universal proximity potential [29] given as

$$\Phi(\epsilon) = -4.41\mathrm{e}^{-\epsilon/0.7176}, \quad \text{for } \epsilon > 1.9475 \tag{4}$$

$$\Phi(\epsilon) = -1.7817 + 0.9270\epsilon + 0.0169\epsilon^2 - 0.05148\epsilon^3, \quad \text{for } 0 \le \epsilon \le 1.9475 \tag{5}$$

with $\epsilon = z/b$, where the width (diffuseness) of the nuclear surface $b \approx 1$ fm and Süssmann central radii C_i of the fragments related to sharp radii R_i is

$$C_i = R_i - \left(\frac{b^2}{R_i}\right). \tag{6}$$

For R_i we use semiempirical formula in terms of mass number A_i as [28]

$$R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}. \tag{7}$$

The potential for the internal part (overlap region) of the barrier is given as

$$V = a_0(L - L_0)^n, \quad \text{for } z < 0, \tag{8}$$

where $L = z + 2C_1 + 2C_2$ and $L_0 = 2C$ is the diameter of the parent nuclei. The constants a_0 and n are determined by the smooth matching of the two potentials at the touching point.

Using one-dimensional WKB approximation, the barrier penetrability P is given as

$$P = \exp\left\{-\frac{2}{\hbar}\int_a^b \sqrt{2\mu(V - Q)}\mathrm{d}z\right\}. \tag{9}$$

Here the mass parameter is replaced by the reduced mass $\mu = mA_1A_2/A$, where m is the nucleon mass and A_1, A_2 are the mass numbers of the daughter and the emitted cluster, respectively. The turning points a and b are determined from the equation, $V(a) = V(b) = Q$. The above integral can be evaluated numerically or analytically, and the half-life is given by

$$T_{1/2} = \left(\frac{\ln 2}{\lambda}\right) = \left(\frac{\ln 2}{\nu P}\right), \tag{10}$$

where $\nu = (\omega/2\pi) = (2E_{\mathrm{v}}/h)$ represents the number of assaults on the barrier per second and λ is the decay constant. E_{v} is the empirical vibration energy and is given as [30]

$$E_{\mathrm{v}} = Q\left\{0.056 + 0.039\exp\left[\frac{(4 - A_2)}{2.5}\right]\right\}, \quad \text{for } A_2 \geq 4. \tag{11}$$

The Coulomb interaction between the two deformed and oriented nuclei with higher multipole deformation included [31,32] is taken from [33] and is given as

$$V_{\mathrm{C}} = \frac{Z_1Z_2e^2}{r} + 3Z_1Z_2e^2 \sum_{\lambda,i=1,2} \frac{1}{2\lambda + 1}\frac{R_{0i}^{\lambda}}{r^{\lambda+1}}Y_{\lambda}^{(0)}(\alpha_i) \times \left[\beta_{\lambda i} + \frac{4}{7}\beta_{\lambda i}^2 Y_{\lambda}^{(0)}(\alpha_i)\delta_{\lambda,2}\right] \tag{12}$$

with

$$R_i(\alpha_i) = R_{0i}\left[1 + \sum_{\lambda}\beta_{\lambda i}Y_{\lambda}^{(0)}(\alpha_i)\right], \tag{13}$$

where $R_{0i} = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}$. Here α_i is the angle between the radius vector and symmetry axis of the ith nuclei (figure 1) and it is to be noted that the quadrupole interaction term proportional to $\beta_{21}\beta_{22}$ is neglected because of its short-range character.

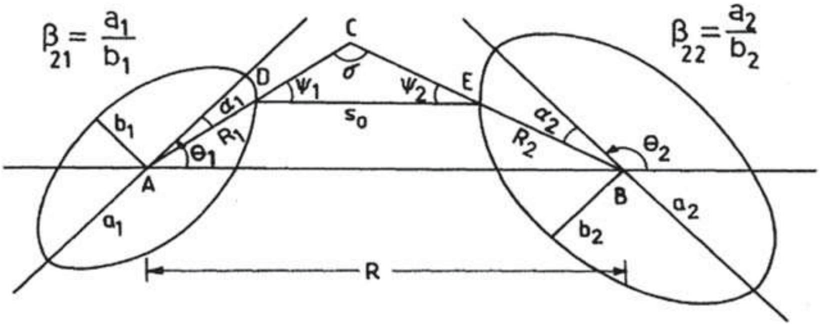

Figure 1. A schematic representation of the configuration of two axially symmetric deformed, oriented nuclei lying in the same plane.

The two-term proximity potential for interaction between a deformed and spherical nucleus is given by Baltz and Bayman [34] as

$$V_{\mathrm{P2}}(R,\theta) = 2\pi \left[\frac{R_1(\alpha)R_{\mathrm{C}}}{R_1(\alpha)+R_{\mathrm{C}}+S}\right]^{1/2} \left[\frac{R_2(\alpha)R_{\mathrm{C}}}{R_2(\alpha)+R_{\mathrm{C}}+S}\right]^{1/2} \times \left[\left[\epsilon_0(S)+\frac{R_1(\alpha)+R_{\mathrm{C}}}{2R_1(\alpha)R_{\mathrm{C}}}\epsilon_1(S)\right]\left[\epsilon_0(S)+\frac{R_2(\alpha)+R_{\mathrm{C}}}{2R_2(\alpha)R_{\mathrm{C}}}\epsilon_1(S)\right]\right]^{1/2}, \tag{14}$$

where $R_1(\alpha)$ and $R_2(\alpha)$ are the principal radii of curvature of the daughter nuclei at the point where polar angle is α, S is the distance between the surfaces along the straight line connecting the fragments, R_{C} is the radius of the spherical cluster, $\epsilon_0(S)$ and $\epsilon_1(S)$ are the one-dimensional slab-on-slab function.

3. Results and discussions

The Coulomb and proximity potential model for deformed nuclei (CPPMDN) was used to evaluate the α decay properties of the isotopes of the SHN with $Z = 115$, 117, 118 and 119, within the range $271 \le A \le 294$, $270 \le A \le 301$, $271 \le A \le 310$ and $274 \le A \le 313$, respectively. The energy released in α transitions between the ground-state energy levels of the parent nuclei and the ground-state energy levels of the daughter nuclei, is given as

$$Q_{\mathrm{gs}\to\mathrm{gs}} = \Delta M_{\mathrm{p}} - (\Delta M_{\alpha} + \Delta M_{\mathrm{d}}) + k(Z_{\mathrm{p}}^{\epsilon} - Z_{\mathrm{d}}^{\epsilon}). \tag{15}$$

Here ΔM_{p}, ΔM_{d} and ΔM_{α} are the mass excesses of the parent, the daughter and the α-particle, respectively. The recent experimental mass table of Wang *et al* [35] was used to evaluate the Q-values for the α decay between the ground state of the parent and the daughter nuclei and for the nuclei whose experimental mass excesses were unavailable, the mass table of Koura–Tachibana–Uno–Yamada (KTUY) [36] was used. As shell effects play a crucial role in giving stability to superheavy nuclei, the shell effects were included in the α decay calculations that come from experimental [35] and/or calculated binding energies [36]. In eq. (15), the term $k(Z_{\mathrm{p}}^{\epsilon} - Z_{\mathrm{d}}^{\epsilon})$ represent the electron screening effect [37], where $k = 8.7$ eV and $\epsilon = 2.517$ for nuclei with $Z \geq 60$ and $k = 13.6$ eV and $\epsilon = 2.408$ for nuclei with $Z \leq 60$. The experimental quadrupole (β_2) and hexadecapole (β_4) deformation values [38] of both the parent and the daughter nuclei were also used for calculating α half-lives. For those nuclei whose experimental deformation values were not available, the theoretical values taken from [39] were used.

The α decay half-lives were evaluated using the Viola–Seborg semiempirical (VSS) relationship [40] and the analytical formulae of Royer [41]. The VSS relationship with constants determined by Sobiczewski *et al* [42] was used for the α half-life calculations and is given as

$$\log_{10}(T_{1/2}) = (aZ + b)Q^{-1/2} + cZ + d + h_{\log}. \tag{16}$$

Here the half-life is in seconds, Q-value is in MeV and Z is the atomic number of the parent nucleus. The constants are $a = 1.66175$, $b = -8.5166$, $c = -0.20228$, $d = -33.9069$ and the quantity $h_{\log}$ represents the hindrances associated with odd proton and odd neutron numbers and are given as

$$\begin{aligned} h_{\log} &= 0.000, && \text{for } Z, N \text{ even}, \\ h_{\log} &= 0.772, && \text{for } Z = \text{odd}, N = \text{even}, \\ h_{\log} &= 1.066, && \text{for } Z = \text{even}, N = \text{odd}, \\ h_{\log} &= 1.114, && \text{for } Z, N \text{ odd}. \end{aligned}$$

The analytical formula for α decay with an RMS deviation of 0.42 was developed by Royer [41] by applying a fitting procedure on a set of 373 α emitters and is given as

$$\log_{10}[T_{1/2}(s)] = -26.06 - 1.114A^{1/6}\sqrt{Z} + \frac{1.5837Z}{\sqrt{Q_\alpha}}. \tag{17}$$

Here A and Z are the mass and charge numbers of the parent nuclei and Q_α is the energy released during the reaction. Assuming the same dependence on the mass and charge of the mother nucleus and experimental Q_α, eq. (17) was adjusted to a subset of 131 even–even nuclei and a relation was obtained with a RMS deviation of only 0.285 and is given as

$$\log_{10}[T_{1/2}(s)] = -25.31 - 1.1629A^{1/6}\sqrt{Z} + \frac{1.5864Z}{\sqrt{Q_\alpha}}. \tag{18}$$

For a subset of 106 even–odd nuclei, the RMS deviation was found to be 0.39, and the relation is given as

$$\log_{10}[T_{1/2}(s)] = -26.65 - 1.0859A^{1/6}\sqrt{Z} + \frac{1.5848Z}{\sqrt{Q_\alpha}}. \tag{19}$$

For a subset of 86 odd–even nuclei, the RMS deviation was found to be 0.36, and the relation is given as

$$\log_{10}[T_{1/2}(s)] = -25.68 - 1.1423A^{1/6}\sqrt{Z} + \frac{1.592Z}{\sqrt{Q_\alpha}}. \tag{20}$$

For a subset of 50 odd–odd nuclei, the RMS deviation was found to be 0.35, and the relation is given as

$$\log_{10}[T_{1/2}(s)] = -29.48 - 1.113A^{1/6}\sqrt{Z} + \frac{1.6971Z}{\sqrt{Q_\alpha}}. \tag{21}$$

The mode of decay of the isotopes under study can be identified through the calculations on spontaneous fission (SF) half-lives of the corresponding nuclei. The semiempirical relation given by Xu *et al* [43], originally made to fit the even–even nuclei, was used for evaluating the SF half-lives, and is given as

$$T_{1/2} = \exp\left[2\pi\left(C_0 + C_1 A + C_2 Z^2 + C_3 Z^4 + C_4 (N-Z)^2 - \left(0.13323\frac{Z^2}{A^{1/3}} - 11.64\right)\right)\right]. \tag{22}$$

Here the constants $C_0 = -195.09227$, $C_1 = 3.10156$, $C_2 = -0.04386$, $C_3 = 1.4030 \times 10^{-6}$ and $C_4 = -0.03199$. It is to be noted that, in the present work, we have considered both even Z (both even–even and even–odd) and odd Z (both odd–even and odd–odd) nuclei. But, as eq. (22) was originally made to fit the even–even nuclei, to calculate the SF half-lives of odd Z nuclei, instead of taking SF half-life (T_{SF}) directly, we have taken the average of fission half-life ($T_{\mathrm{SF}}^{\mathrm{av}}$) of the corresponding neighbouring even–even nuclei as the case may be. While dealing with the odd–even nuclei, we have taken $T_{\mathrm{SF}}^{\mathrm{av}}$ of four neighbouring even–even nuclei and for odd–odd nuclei, $T_{\mathrm{SF}}^{\mathrm{av}}$ of six neighbouring even–even nuclei was taken.

The details of the study on α decay and the predictions on the mode of decay of the recently synthesized superheavy elements $^{287,288}115$, $^{293,294}117$ and $^{294}118$ and their α decay products are given in table 1. In column 1, the isotope under study and their corresponding α decay chains are given. Column 2 gives the respective Q-values of the isotopes evaluated using eq. (15) and the SF half-lives of isotopes under study are given in column 3. In column 4, the experimental α half-lives [44–46] of the isotopes are given and the α decay half-lives of the isotopes evaluated within the CPPMDN formalism are given in column 5. The calculations were carried out using the CPPM formalism, excluding the quadrupole (β_2) and hexadecapole (β_4) deformation values of both the parent and the daughter nuclei, and is given in column 6. The half-life calculations done using the VSS relationship and the analytical formula of Royer are given in columns 7 and 8, respectively. It can be seen that our calculations are in good agreement with the theoretical values. The predictions on the mode of decay of isotopes are depicted in column 9 and as can be seen, our predictions match well with the experimentally observed facts. Here we would like to mention that, in the case of $Z = 117$, the experimental result shows 6α chains for $^{294}117$, which differs from our present theoretical prediction of four consistent α chains. So, for a more accurate prediction, a different method of calculating the SF half-lives was adopted. Within a dynamical approach [6,47] without any adjustable parameters, the SF half-lives of even–even nuclei with $Z = 104-114$ have already been analysed in a multidimensional deformation space. As the results could reproduce the existing experimental data rather well, we have adopted these values and thus $T_{\mathrm{SF}}^{\mathrm{av}}$ were calculated. Using these values we could predict 6α chains for $^{294}117$ and these results have already been presented in our earlier work [20]. As an extension to the studies on the α decay of the experimentally synthesized superheavy nuclei, we have also studied [22] the α decay properties of the isotopes of the yet to be synthesized $Z = 119$ superheavy nuclei. Through our study, we would like to highlight the decay chains of $^{292-299}119$ isotopes. We could observe 6α chains from $^{292-295}119$, 5α chains from $^{296}119$, 4α chains

Table 1. Alpha decay half-lives of $^{287,288}115$, $^{293,294}117$ and $^{294}118$ and their decay products are compared with the corresponding experimental α half-lives [44–46]. The calculations are done for zero angular momentum transfers.

Parent nuclei	Q_α (cal) MeV	T_{SF} (s)	$T^{\alpha}_{1/2}$(s)					Decay mode
			Expt.	CPPMDN	CPPM	VSS	Royer	
$^{287}115$	11.36	5.94×10^{4}	3.20×10^{-2}	1.01×10^{-3}	3.95×10^{-3}	5.89×10^{-3}	1.51×10^{-3}	$\alpha1$
$^{283}113$	10.65	2.35×10^{1}	1.00×10^{-1}	1.58×10^{-2}	6.80×10^{-2}	8.60×10^{-2}	2.14×10^{-2}	$\alpha2$
$^{279}111$	10.51	1.35×10^{-1}	1.70×10^{-1}	7.89×10^{-3}	3.53×10^{-2}	4.81×10^{-2}	1.16×10^{-2}	$\alpha3$
^{275}Mt	10.17	9.49×10^{-3}	9.70×10^{-3}	7.87×10^{-3}	6.58×10^{-2}	8.88×10^{-2}	2.10×10^{-2}	$\alpha4$
^{271}Bh	9.56	7.58×10^{-3}	–	5.20×10^{-2}	8.40×10^{-1}	9.61×10^{-1}	2.26×10^{-1}	SF
$^{288}115$	11.06	3.13×10^{4}	8.70×10^{-2}	6.66×10^{-3}	2.32×10^{-2}	6.91×10^{-2}	1.94×10^{-1}	$\alpha1$
$^{284}113$	10.30	1.23×10^{1}	4.80×10^{-1}	1.10×10^{-1}	6.48×10^{-1}	1.59×10^{0}	5.38×10^{0}	$\alpha2$
$^{280}111$	10.04	7.00×10^{-1}	3.60×10^{0}	2.16×10^{-1}	7.60×10^{-1}	1.91×10^{0}	6.04×10^{0}	$\alpha3$
^{276}Mt	9.85	5.00×10^{-3}	7.20×10^{-1}	9.41×10^{-2}	5.53×10^{-1}	1.46×10^{0}	4.18×10^{0}	SF
$^{293}117$	11.73	3.99×10^{4}	1.40×10^{-2}	1.19×10^{-3}	1.90×10^{-3}	2.95×10^{-3}	7.28×10^{-4}	$\alpha1$
$^{289}115$	10.65	3.68×10^{4}	2.20×10^{-1}	1.27×10^{-1}	3.04×10^{-1}	3.50×10^{-1}	8.37×10^{-2}	$\alpha2$
$^{285}113$	10.08	5.24×10^{2}	5.50×10^{0}	5.81×10^{-1}	2.82×10^{0}	2.92×10^{0}	6.79×10^{-1}	$\alpha3$
$^{281}111$	9.69	1.03×10^{0}	2.60×10^{1}	1.93×10^{0}	8.57×10^{0}	8.55×10^{0}	1.94×10^{0}	SF
$^{294}117$	12.20	1.31×10^{7}	7.80×10^{-2}	9.85×10^{-4}	1.33×10^{-4}	5.70×10^{-4}	2.11×10^{-4}	$\alpha1$
$^{290}115$	10.35	1.30×10^{3}	1.60×10^{-2}	1.63×10^{0}	2.15×10^{0}	4.91×10^{0}	3.00×10^{0}	$\alpha2$
$^{286}113$	9.74	6.26×10^{4}	2.00×10^{1}	6.45×10^{0}	3.05×10^{1}	6.09×10^{1}	3.97×10^{1}	$\alpha3$
$^{282}111$	9.43	3.26×10^{2}	5.10×10^{-1}	1.03×10^{1}	5.60×10^{1}	1.12×10^{2}	6.86×10^{1}	$\alpha4$
^{278}Mt	9.16	1.24×10^{0}	7.70×10^{0}	1.51×10^{1}	7.84×10^{1}	1.58×10^{0}	9.01×10^{1}	SF
$^{294}118$	11.82	3.05×10^{8}	8.90×10^{-4}	1.94×10^{-3}	6.21×10^{-4}	2.02×10^{-4}	3.76×10^{-4}	$\alpha1$
^{290}Lv	10.99	6.39×10^{3}	7.10×10^{-3}	2.15×10^{-2}	1.56×10^{-2}	4.52×10^{-3}	9.20×10^{-3}	$\alpha2$
^{286}Fl	10.37	2.37×10^{0}	1.29×10^{-1}	2.11×10^{-1}	1.70×10^{-1}	4.68×10^{-2}	9.84×10^{-2}	$\alpha3$
^{282}Cn	10.12	1.28×10^{-2}	–	2.09×10^{-1}	1.90×10^{-1}	5.47×10^{-2}	1.10×10^{-1}	SF

from $^{297}119$ and 3α chains from $^{298,299}119$, by comparing the α decay half-lives with that of the SF half-lives.

Thus, our study [18–22] on isotopes having $Z = 115$, 117, 118 and 119 reveals some interesting facts on the range of isotopes that may be detectable through α decay. In the case of $Z = 115$ superheavy nuclei, all those isotopes with $A \leq 271$ and $A \geq 292$ do not survive fission and thus the α decay is restricted within the range $272 \leq A \leq 291$. While considering the isotopes of $Z = 117$, it is seen that those isotopes with $A \leq 271$ and $A \geq 299$ do not survive fission and thus the α decay is restricted within the range $272 \leq A \leq 298$. In the case of $Z = 118$ and 119 superheavy nuclei, the α decay is restricted within the range $276 \leq A \leq 300$ and $276 \leq A \leq 308$, respectively.

4. Conclusion

The CPPMDN formalism was used to study the α decay properties of isotopes of $Z = 115$, 117, 118 and 119, focussing on the recently synthesized isotopes $^{287,288}115$,

^{293,294}117 and ^{294}118. The half-lives were also evaluated using the CPPM formalism, the Viola–Seaborg systematic (VSS) and the analytical formulae of Royer. The calculated values match well with the theoretical values and it is to be noted that the inclusion of deformation values decreases the α decay half-lives. The calculations on spontaneous fission half-lives have helped in studying the mode of decay of the isotopes under study. Our predictions of 4α chains from ^{287}115, 3α chains from ^{288}115, 3α chains from ^{293}117, 4α chains from ^{294}117 and 3α chains from ^{294}118 can be seen to be in good agreement with the experimental observations. Thus, it is noteworthy that our observations and predictions on the α decay half-lives and mode of decay of the isotopes go hand-in-hand with the experimental results. A detailed study on the isotopes of the yet to be synthesized superheavy nuclei $Z = 119$ has also been done and we hope that our predictions on the $^{292-299}$119 isotopes may be of great use in future experiments.

References

[1] S S Hofmann and G Münzenberg, *Rev. Mod. Phys.* **72**, 733 (2000)
[2] K Morital *et al*, *J. Phys. Soc. Jpn* **73**, 2593 (2004)
[3] Yu Ts Oganessian, *J. Phys. G: Nucl. Part. Phys.* **34**, R165 (2007)
[4] M A Stoyer, *Nature* **442**, 876 (2006)
[5] P Moller and J R Nix, *Nucl. Phys. A* **549**, 84 (1992)
[6] R Smolanczuk, J Skalski and A Sobiczewski, *Phys. Rev. C* **52**, 1871 (1995)
[7] D N Poenaru, I H Plonski and W Greiner, *Phys. Rev. C* **74**, 014312 (2006)
[8] D S Delion, R J Liotta and R Wyss, *Phys. Rev. C* **76**, 044301 (2007)
[9] P R Chowdhury, C Samanta and D N Basu, *Phys. Rev. C* **77**, 044603 (2008)
[10] Z Ren and C Xu, *J. Phys.: Conf. Ser.* **111**, 012040 (2008)
[11] S Kumar, S Thakur and R Kumar, *J. Phys. G: Nucl. Part. Phys.* **36**, 105104 (2009)
[12] A Sobiczewski, *Acta Phys. Pol. B* **41**, 157 (2010)
[13] P R Chowdhury, G Gangopadhyay and A Bhattacharyya, *Phys. Rev. C* **83**, 027601 (2011)
[14] V Yu Denisov and A A Khudenko, *Phys. Rev. C* **81**, 034613 (2010)
[15] K P Santhosh, S Sabina and G J Jayesh, *Nucl. Phys. A* **850**, 34 (2011)
[16] K P Santhosh, S Sabina and R K Biju, *Nucl. Phys. A* **825**, 159 (2009)
[17] K P Santhosh and S Sabina, *Phys. At. Nucl.* **75**, 973 (2012)
[18] K P Santhosh, B Priyanka, G J Jayesh and S Sabina, *Phys. Rev. C* **84**, 024609 (2011)
[19] K P Santhosh, B Priyanka and M S Unnikrishnan, *Phys. Rev. C* **85**, 034604 (2012)
[20] K P Santhosh and B Priyanka, *J. Phys. G: Nucl. Part. Phys.* **39**, 085106 (2012)
[21] K P Santhosh and B Priyanka, *Phys. Rev. C* **87**, 064611 (2013)
[22] K P Santhosh and B Priyanka, *Phys. Rev. C* **89**, 064604 (2014)
[23] K P Santhosh, S Sabina, B Priyanka and M S Unnikrishnan, *Nucl. Phys. A* **882**, 49 (2012)
[24] K P Santhosh and B Priyanka, *Nucl. Phys. A* **929**, 20 (2014)
[25] K P Santhosh and A Joseph, *Pramana – J. Phys.* **55**, 375 (2000)
[26] K P Santhosh and A Joseph, *Pramana – J. Phys.* **58**, 611 (2002)
[27] Y J Shi and W J Swiatecki, *Nucl. Phys. A* **438**, 450 (1985)
[28] J Blocki, J Randrup, W J Swiatecki and C F Tsang, *Ann. Phys. (NY)* **105**, 427 (1977)
[29] J Blocki and W J Swiatecki, *Ann. Phys. (NY)* **132**, 53 (1981)
[30] D N Poenaru, M Ivascu, A Sandulescu and W Greiner, *Phys. Rev. C* **32**, 572 (1985)
[31] N Malhotra and R K Gupta, *Phys. Rev. C* **31**, 1179 (1985)
[32] R K Gupta, M Balasubramaniam, R Kumar, N Singh, M Manhas and W Greiner, *J. Phys. G: Nucl. Part. Phys.* **31**, 631 (2005)

[33] C Y Wong, *Phys. Rev. Lett.* **31**, 766 (1973)
[34] A J Baltz and B F Bayman, *Phys. Rev. C* **26**, 1969 (1982)
[35] M Wang, G Audi, A H Wapstra, F G Kondev, M MacCormick, X Xu and B Pfeiffer, *Chin. Phys. C* **36**, 1603 (2012)
[36] H Koura, T Tachibana, M Uno and M Yamada, *Prog. Theor. Phys.* **113**, 305 (2005)
[37] V Y Denisov and H Ikezoe, *Phys. Rev. C* **72**, 064613 (2005)
[38] http://www-nds.iaea.org/RIPL-2/
[39] P Moller, J R Nix and K L Kratz, *At. Data Nucl. Data Tables* **66**, 131 (1997)
[40] V E Viola Jr and G T Seaborg, *J. Inorg. Nucl. Chem.* **28**, 741 (1966)
[41] G Royer, *J. Phys. G: Nucl. Part. Phys.* **26**, 1149 (2000)
[42] A Sobiczewski, Z Patyk and S Cwiok, *Phys. Lett. B* **224**, 1 (1989)
[43] C Xu, Z Ren and Y Guo, *Phys. Rev. C* **78**, 044329 (2008)
[44] Yu Ts Oganessian *et al*, *Phys. Rev. C* **69**, 021601(R) (2004)
[45] Yu Ts Oganessian *et al*, *Phys. Rev. C* **83**, 054315 (2011)
[46] Yu Ts Oganessian *et al*, *Phys. Rev. Lett.* **109**, 162501 (2012)
[47] R Smolanczuk, *Phys. Rev. C* **56**, 812 (1997)