Alpha decay chains of superheavy nuclei

K. P. Santhosh
School of Pure and Applied Physics, Kannur University, Swami Anandatheertha Campus, Payyanur - 670327, Kerala, INDIA
** email: drkpsanthosh@gmail.com*

Introduction

A scientific knowledge on the nuclear stability in the superheavy mass region is a long-standing question. Hence, considerable attention has been given by the experimentalists to the investigation of the existence of superheavy nuclei (SHN) beyond the valley of stability. The half lives of different radioactive decay such as alpha decay and spontaneous fission are the experimental signatures of the formation of SHN in fusion reaction. Hence, the calculations of these half-lives are important in identifying the decay chains of SHN. The existence of SHN is controlled mainly by spontaneous fission and α decay processes. Hence identifying and characterizing the α decay chains form a crucial part of nuclide identification in the synthesis of SHN.

In this paper we have presented a systematic study on the feasibility of observing alpha decay chains from the isotopes of the superheavy nuclei with Z = 115, 117, 118, 119 and 120 has been performed using the recently proposed Coulomb and proximity potential model for deformed nuclei (CPPMDN) [1], the modified version of CPPM (Coulomb and proximity potential model) [2] incorporating quadrupole (β_2) and hexadecapole (β_4) deformation values of the both parent and daughter nuclei.

The Model

The potential energy barrier in CPPMDN is taken as the sum of deformed Coulomb potential, deformed two-term proximity potential and the centrifugal potential, for the touching configuration and for the separated fragments. For the pre-scission region, a simple power law interpolation was used.

The Coulomb interaction between the two deformed and oriented nuclei is given as,

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

with (1)

$$R_i(\alpha_i)=R_{0i}\left[1+\sum_{\lambda}\beta_{\lambda i}Y_{\lambda}^{0}(\alpha_i)\right] \tag{2}$$

Here $R_{0i}=1.28A_i^{1/3}-0.76+0.8A_i^{-1/3}$ where α_i is the angle between the radius vector and symmetry axis of the i^{th} nuclei. The two-term proximity potential for interaction between a deformed and spherical nucleus is given by Baltz et. al., as

$$V_{P2}(R,\theta)=2\pi\left[\frac{R_1(\alpha)R_C}{R_1(\alpha)+R_C+S}\right]^{1/2}\left[\frac{R_2(\alpha)R_C}{R_2(\alpha)+R_C+S}\right]^{1/2}\times$$

$$\left[\left[\varepsilon_0(S)+\frac{R_1(\alpha)+R_C}{2R_1(\alpha)R_C}\varepsilon_1(S)\right]\left[\varepsilon_0(S)+\frac{R_2(\alpha)+R_C}{2R_2(\alpha)R_C}\varepsilon_1(S)\right]\right]^{1/2} \tag{3}$$

Here $R_1(\alpha)$ 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, $\varepsilon_0(S)$ and $\varepsilon_1(S)$ are the one dimensional slab-on-slab function. Using one dimensional WKB approximation, the barrier penetrability P is given as

$$\mathrm{P}=\exp\left\{-\frac{2}{\hbar}\int_a^b\sqrt{2\mu(V-Q)}dz\right\} \tag{4}$$

The turning points "a" and "b" are determined from the equation, $V(a)=V(b)=Q$. The half life time is given by

$$T_{1/2}=\left(\frac{\ln 2}{\lambda}\right)=\left(\frac{\ln 2}{\nu P}\right) \tag{5}$$

where, $\nu=(\omega/2\pi)=(2E_\nu/h)$, represents the number of assaults on the barrier per second and λ the decay constant. E_ν, is the empirical vibration energy.

Results and Discussion

Within CPPMDN, an extensive study on the feasibility of alpha decay from the isotopes of $^{271-294}115$, $^{270-301}117$, $^{271-310}118$, $^{274-313}119$ and $^{272-319}120$ have been done. The energy released in the alpha transitions between the ground state energy levels of the parent nuclei and the ground state energy levels of the daughter nuclei is given as

$$Q_{gs\to gs}=\Delta M_p-(\Delta M_\alpha+\Delta M_d)+k(Z_p^{\varepsilon}-Z_d^{\varepsilon}) \tag{6}$$

where ΔM_p, ΔM_d, ΔM_α are the mass excess of the parent, daughter and alpha particle respectively. The Q values are evaluated using the mass excess values taken from Wang et al., and Koura-Tachibana-Uno-Yamada (KTUY). The term kZ^{ε} represents the screening effect of atomic electrons.

Now, to identify the mode of decay of the isotopes under study, the spontaneous fission (SF) half lives have also been evaluated using the semi empirical relation of Xu *et al.*, given as

$$T_{1/2}=\exp\left\{2\pi\left[C_0+C_1A+C_2Z^2+C_3Z^4+C_4(N-Z)^2-(0.13323\frac{Z^2}{A^{1/3}}-11.64)\right]\right\}$$

As this equation was originally made to fit the even-even nuclei, and as we have considered the odd mass (odd-even and odd-odd) nuclei, instead of taking spontaneous fission half life directly, we have taken the average of fission half life of the corresponding neighboring even-even nuclei as the case may be and our calculations show the agreement between experimental and computed average spontaneous fission half lives. Thus, those isotopes with small alpha decay half lives than the spontaneous fission half lives survive fission and hence can be detected through alpha decay in the laboratory. Thus by comparing the alpha decay half lives with the spontaneous fission half lives, we could identify the nuclei (both parent and decay products) that will survive fission.

The alpha decay half lives of $^{271\text{-}294}$115 superheavy nuclei, including the recently synthesized ^{287}115 and ^{288}115 have been calculated [3] within CPPMDN. On comparing the alpha decay half lives with the spontaneous fission half lives, we could predict 4α chains from ^{287}115 and 3α chains from ^{288}115. As one may notice, our prediction agrees well with the experimental observations and it is also to be noted that the alpha half lives calculated using our formalisms matches well with the experimental alpha half lives. As we could successfully reproduce the experimental results in the case of ^{287}115 and ^{288}115, we have confidently extended our work in predicting the α decay half lives of 22 more superheavy elements of Z = 115 with a view to find possible alpha decay chains and our study predicts 2*α* chains from ^{273,274,289}115, 3*α* chains from ^{275,292}115, 4*α* chains consistently from ^{284,285,286}115 nuclei and 5α chains consistently from $^{288\text{-}291}$117. We hope that these findings will provide a new guide for future experiments.

The alpha decay half lives of SHN with Z = 117 have been evaluated [4,5] in a similar manner as mentioned above within CPPMDN. We have predicted 3α chains for ^{293}117 and 6α chains for ^{294}117 and it can be seen that our predictions go hand in hand with the experimental observations. Now, we have confidently extended our work in predicting the α decay half lives of 32 more superheavy elements of Z = 117 and our study reveals that those isotopes of Z = 117 with A ≥ 299 and with A ≤ 271, do not survive fission and thus the alpha decay is restricted within the range 272 ≤ A ≤ 298. Through our study, we have predicted 1α chain from $^{272,273,296\text{-}298}$117, 2α chains from ^{274,275,295}117, 3α chains from ^{276,277,292}117 and 5α chains from $^{288\text{-}291}$117.

The alpha decay half lives of SHN with Z = 118 and Z = 119 have also been evaluated [6,7] in a similar manner within CPPMDN. The α decay half-lives and the mode of decay of ^{294}118 evaluated using our formalisms, were found to be in good agreement with the experimental results. Now, we have confidently extended our work in predicting the α decay half lives of 39 more superheavy elements of Z = 118 and our study reveals that those isotopes of Z = 118 with A ≥ 301 and with A ≤ 275, do not survive fission and thus the alpha decay is restricted within the range 276 ≤ A ≤ 300. Through our study, we have predicted 1α chain from $^{276,298\text{-}300}$118, 2α from $^{277,278,295\text{-}297}$118 and 5α chains from $^{289\text{-}293}$118. Even though we could observe consistent 3α, 4α, and 6α chains from ^{279,280}118, ^{281}118, and ^{282,283}118, respectively, these nuclei could not be predicted to be synthesized in the laboratories as their decay half-lives are too small, which span the order 10^{-9}s to 10^{-6}s. The study on $^{274\text{-}313}$119 helps to identify the mode of decay of about 40 isotopes with Z = 119. Our reveals that those isotopes of Z = 119 with A ≥ 309 and with A ≤ 275 do not survive fission, and thus, the α decay is restricted within the range of 276 ≤ A ≤ 308. Through our study, we have predicted 6 consistent α chains from $^{292\text{-}295}$119, 5 consistent α chains from ^{296}119, 4 consistent α chains from ^{297}119, and 3 consistent α chains from ^{298,299}119 which will be a new guide for future experiments.

The predictions on the α decay chains of $^{272\text{-}319}$120 SHN have also been done [8] within CPPMDN. The study reveals that the α decay half lives and the mode of decay of the isotopes of the experimentally synthesized SHN ^{298,299}120 evaluated using our formalism agree well with the experimental observations. Our study on predicts that the α decay is restricted within the range 277 ≤ A ≤ 308 as those isotopes with A ≤ 276 and those nuclei with A ≥ 309 do not survive fission. We have also forecasted the mode of decay of $^{288\text{-}302}$120 superheavy nuclei as 6α chains from the nuclei of $^{288,289,291\text{-}295}$120, 7α chains from ^{290}120, 5α chains from ^{296,297}120, and 3α chains from $^{300\text{-}302}$120, which could be of great interest to the experimentalists.

The alpha half life calculations have also been done using the CPPM formalism, the Viola-Seborg semi-empirical relationship (VSS), the Universal curve (UNIV) of Poenaru et al., and the analytical formulae of Royer and it could be seen that the alpha decay half lives evaluated using our formalism agrees well with the values evaluated using these theoretical formalisms.

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