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Theoretical predictions for α-decay chains of $Z = 119$ isotopes in the region $274 \leqslant A \leqslant 313$

K. P. Santhosh* and B. Priyanka

School of Pure and Applied Physics, Kannur University, Swami Anandatheertha Campus, Payyanur 670 327, Kerala, India

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An extensive study on the α-decay half-life for the isotopes of $Z = 119$ superheavy nuclei in the range $274 \leqslant A \leqslant 313$ is performed within the Coulomb and proximity potential model for deformed nuclei (CPPMDN). We have also evaluated the decay properties by keeping the parents and daughter in spherical nuclear shape (without including the nuclear deformations), within the Coulomb and proximity potential model (CPPM). The half-life calculations are also performed by using the Viola-Seborg semi-empirical (VSS) relation, very frequently used for α-decay studies, and it can be seen that our predictions agree well with the computed VSS values. Our intention to understand the mode of decay of the isotopes was fulfilled through the spontaneous fission (SF) half-life calculations and the comparison of the α half-lives with the SF half-lives. Thus, our study reveals that those isotopes of $Z = 119$ with $A \geqslant 309$ and with $A \leqslant 275$ do not survive fission, and thus, the α decay is restricted within the range of $276 \leqslant A \leqslant 308$. Through our study, we have predicted six consistent α chains from $^{292-295}119$, five consistent α chains from $^{296}119$, four consistent α chains from $^{297}119$, and three consistent α chains from $^{298,299}119$, and we hope these findings will provide a new guide for future experiments. A theoretical study is performed here to understand the mode of decay of the isotopes of $Z = 119$, which helps to identify the mode of decay of about 40 isotopes within the range of $274 \leqslant A \leqslant 313$.

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I. INTRODUCTION

The availabilities and advancements in stable nuclear beam technology have resulted in the fast growth of the nuclear chart especially in the superheavy (SH) mass region. The production of the proton-rich isotopes of superheavy elements up to $Z = 113$ is an outgrowth of the "cold" fusion reactions [1–6] based on the use of lead and bismuth targets. The "hotter" fusion reactions [7–15] of ^{48}Ca with actinide targets have helped in the synthesis of more neutron-rich isotopes of SH elements (up to $Z = 118$). The heaviest element known so far is $Z = 118$ [4,11], and any further progress in the synthesis of new elements with $Z > 118$ is not quite evident. The synthesis and identification of new SH elements have emerged as a hot topic in nuclear physics as the question on the border of the elements' existence is still unanswered. The short lifetimes and the low production cross sections of the SH elements have posed difficulties to both experimentalists and theoreticians in studying the various properties of SH elements. The indication on the strong shell effects in the SH area of the nuclear map is evident from the variation in the half-lives of different isotopes of the same SH element (for example, $Z = 112$) by several orders of magnitude. But a theoretical understanding of these effects and several other properties of SH nuclei is strongly impeded due to the absence of experimental data on decay properties of the not-yet-synthesized neutron-enriched isotopes of these elements [14].

The new exciting experimental [13–15] studies on the SH region draw theoretical attention to understand the nuclear structure of the parent as well as of the daughter nucleus and, hence, to obtain information about the *island of stability* beyond $Z = 82$, $N = 126$. The superheavy nuclei usually undergo spontaneous decay into successive α-decay chains, which lead to known isotopes before spontaneous fission. Even though β decay is another possible decay mode for the superheavy nuclei, as it proceeds *via* a weak interaction, the process is slow and is less favored compared to spontaneous fission and α decay. The α-decay energy and half-lives of these decay chains help us to identify a new region of isotopes already located close to the expected superheavy nuclei. But the experimental difficulty is that the observed nuclides decay over long α-decay chains, which ends in spontaneous fission and, hence, these form an island of nuclei in itself and cannot be connected to the known region of isotopes [16]. Hence, an unambiguous identification with the presently used parent-daughter method becomes impossible, which forces experimentalists to carry out a number of consistency checks [9].

The theoretical studies, especially on α decays in the superheavy region, are closely related to nuclear model predictions [17–19], such as clustering, shell structures, deformations, and quasiparticle excitations, and various methods have been developed for investigating the α-decay properties in the superheavy mass region. The structure and properties of the known SH elements have been investigated extensively by using various approaches, which consist of the microscopic nature, such as nonrelativistic density-dependent Skyrme-Hartree-Fock theory [20], the relativistic mean-field theory [21–24], or the macroscopic-microscopic type [25,26]. The semiempirical Viola-Seaborg formula [27], most commonly adopted by both experimentalists and theoreticians for the study of α decay, has been successful in explaining the decay properties but contains no structure information. So, for a more precise description, one has to resort to the cluster tunneling model or the Gamow model in which the tunneling probability is calculated by the Wentzel-Kramers-Brillouin (WKB) method. The Coulomb and proximity potential model (CPPM) proposed by Santhosh and Joseph [28,29] and its

*drkpsanthosh@gmail.com

modified version, the Coulomb and proximity potential model for deformed nuclei (CPPMDN) [30] are two such approaches where Gamow's idea of quantum-mechanical tunneling is used. The inclusion of the zero-point vibration energy, usage of correct barrier heights, which include centrifugal contribution, are some of the virtues of our models apart from the usage of the two realistic potentials. The versatility of the modified version of the CPPM, the CPPMDN, is the incorporation of the deformations of the parents and the daughters and their spins. The CPPM has been very successful in describing various cluster emissions and α-decay studies of both heavy [31–34] and superheavy [35–40] elements. The validity and applicability of the CPPMDN has also been proved through our recent studies on the α transitions from both the ground state and the isomeric states [41], α fine structure studies of even-even [30], even-odd [42], odd-even [43] and odd-odd [44] nuclei, and the α-decay studies of the superheavy elements $Z = 115$ [38] and $Z = 117$ [39,40].

The goal of the present paper is to study the decay properties and mode of decay of the isotopes of the yet-to-be-synthesized SH element $Z = 119$ within the recently proposed CPPMDN. The predictions on the possibilities on the discovery of $^{299}119$ by Zagrebaev *et al.*, [14], the calculations on the evaporation residue cross sections in reactions that lead to the formation of $^{295,296}119$ SH elements by means of the modified fusion-by-diffusion model [45], and the theoretical predictions on $^{299}119$ by using the SK model [46] are some of the recent studies on the isotopes of $Z = 119$. Thus, the theoretical and experimental predictions on the SH element 119, the most hopeful new element with $Z > 118$ to be synthesized in the near future, were the inspirations for our study.

In Sec. II, we have presented the details of the CPPMDN, results and discussions on the α decay and spontaneous fission of the nuclei under study are given in Sec. III, and a conclusion on the entire paper is given in Sec. IV.

II. CPPMDN

In the CPPMDN, for the touching configuration and for the separated fragments, the potential-energy barrier is taken as the sum of the deformed Coulomb potential, the deformed two-term proximity potential, and the centrifugal potential. For the prescission (overlap) region, simple power-law interpolation, as performed by Shi and Swiatecki [47], is used. The inclusion of the proximity potential reduces the height of the potential barrier, which closely agrees with the experimental result.

The proximity potential was first used by Shi and Swiatecki [47] in an empirical manner and has been quite extensively used for over a decade by Malik *et al.* [48] in the preformed cluster model. Dutt and Puri [49,50] have been using different versions of the proximity potential for studying fusion cross sections of different target-projectile combinations. In our model, the contribution of both internal and external parts of the barrier is considered for the penetrability calculation. In the present model assault frequency, ν is calculated for each parent-cluster combination which is associated with vibration energy. But Shi and Swiatecki [51] get ν empirically unrealistic values 10^{22} for even-A parents and 10^{20} for odd-A parents.

The interacting potential barrier for two spherical nuclei is given by

$$V = \frac{Z_1 Z_2 e^2}{r} + V_p(z) + \frac{\hbar^2 \ell(\ell+1)}{2\mu r^2} \quad \text{for} \quad z > 0. \qquad (1)$$

Here, Z_1 and Z_2 are the atomic numbers of the daughter and emitted cluster, z is the distance between the near surfaces of the fragments, r is the distance between fragment centers, ℓ represents the angular momentum, μ is the reduced mass, V_p is the proximity potential given by Blocki *et al.* [52] as

$$V_p(z) = 4\pi\gamma b \left[\frac{C_1 C_2}{(C_1 + C_2)}\right] \Phi\left(\frac{z}{b}\right). \qquad (2)$$

With the nuclear surface tension coefficient,

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

where N, Z, and A represent neutron, proton, and mass numbers of the parent and Φ represents the universal proximity potential [53] given as

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

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

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

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

For R_i, we use a semiempirical formula in terms of mass number A_i as [52]

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

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

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

where $L = z + 2C_1 + 2C_2$ and $L_0 = 2C$, 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.

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

$$P = \exp\left\{-\frac{2}{\hbar}\int_a^b \sqrt{2\mu(V-Q)}\,dz\right\}. \qquad (9)$$

Here, the mass parameter is replaced by $\mu = mA_1A_2/A$, where m is the nucleon mass and A_1, A_2 are the mass numbers of the daughter and emitted clusters, 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 time is given by

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

where $\nu = (\frac{\omega}{2\pi}) = (\frac{2E_v}{h})$ represents the number of assaults on the barrier per second and λ represents the decay constant. E_v, the empirical vibration energy, is given as [54]

$$E_v = Q\left\{0.056 + 0.039\exp\left[\frac{(4-A_2)}{2.5}\right]\right\} \quad \text{for} \quad A_2 \geqslant 4. \tag{11}$$

In the classical method, the α particle is assumed to move back and forth in the nucleus, and the usual way of determining the assault frequency is through the expression given by $\nu = velocity/(2R)$, where R is the radius of the parent nuclei. But the α particle has wave properties; therefore, a quantum-mechanical treatment is more accurate. Thus, by assuming that the α particle vibrates in a harmonic oscillator potential with a frequency ω, which depends on the vibration energy E_v, we can identify this frequency as the assault frequency ν given in Eqs. (10) and (11).

The Coulomb interaction between the two deformed and oriented nuclei, taken from Ref. [55], with higher multipole deformation included [56,57] is given as

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

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 the symmetry axis of the i^{th} nuclei (see Fig. 1 of Ref. [56]). Note that the quadrupole interaction term proportional to $\beta_{21}\beta_{22}$ is neglected because of its short-range character.

Nuclear interaction [58,59] can be taken into two variants: the proximity potential and the double folding potential. The latter is more effective in the description of the interaction between two fragments. The proximity potential of Blocki *et al.* [52] and Blocki and Swiatecki [53] has one term based on the first approximation of the folding procedure, which describes the interaction between two pure spherically symmetric fragments. The two-term proximity potential of Baltz and Bayman (Eq. (11) of Ref. [60]) includes the second component as the second approximation of the more accurate folding procedure. The authors have shown that the two-term proximity potential is in excellent agreement with the folding model for a heavy-ion reaction not only in shape, but also in absolute magnitude (see Fig. 3 of Ref. [60]). The two-term proximity potential for the interaction between a deformed and a spherical nucleus is given by Baltz and Bayman [60] as

$$V_{p2}(R,\theta) = 2\pi\left[\frac{R_1(\alpha)R_C}{R_1(\alpha)+R_C+S}\right]^{1/2}\left[\frac{R_2(\alpha)R_C}{R_2(\alpha)+R_C+S}\right]^{1/2} \times\left\{\left[\varepsilon_0(S) + \frac{R_1(\alpha)+R_C}{2R_1(\alpha)R_C}\varepsilon_1(S)\right] \times\left[\varepsilon_0(S) + \frac{R_2(\alpha)+R_C}{2R_2(\alpha)R_C}\varepsilon_1(S)\right]\right\}^{1/2}. \tag{14}$$

Here, $R_1(\alpha)$ and $R_2(\alpha)$ are the principal radii of the curvature of the daughter nuclei at the point where the 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, and $\varepsilon_0(S)$ and $\varepsilon_1(S)$ are the one-dimensional slab-on-slab functions.

III. RESULTS AND DISCUSSIONS

The study on the possibilities of α decay from the isotopes of the superheavy element $Z = 119$ has been performed within the CPPMDN. We were confident to carry out this study as the α-decay properties and the mode of decay of both $Z = 115$ and $Z = 117$ have already been analyzed [38–40] by using our models. The α-decay half-lives of the isotopes of $Z = 119$ in the range of $274 \leqslant A \leqslant 313$ are performed here. The CPPMDN takes the external drifting potential as the sum of the deformed Coulomb potential, the deformed two-term proximity potential, and the centrifugal potential. During the α transitions between the ground-state energy levels of the parent nuclei and the ground-state energy levels of the daughter nuclei, the energy released is given as

$$Q_{gs\to gs} = \Delta M_p - (\Delta M_\alpha + \Delta M_d) + k\left(Z_p^{\varepsilon} - Z_d^{\varepsilon}\right), \tag{15}$$

where $\Delta M_p, \Delta M_d$, and ΔM_α are the mass excess of the parent, the daughter, and the α particle, respectively. We have evaluated the Q values for α decay by using the experimental mass excess values of Wang *et al.* [61], and some of the mass excesses were taken from Koura-Tachibana-Uno-Yamada [62] as those experimental mass excesses were unavailable in Ref. [61]. As the effect of atomic electrons on the energy of the α particle has not been included in Refs. [61,62], for a more accurate calculation of the Q value, we have included the electron screening effect [63] in Eq. (15). The term $k(Z_p^{\varepsilon} - Z_d^{\varepsilon})$ represents this correction where $k = 8.7$ eV and $\varepsilon = 2.517$ for nuclei with $Z \geqslant 60$ and $k = 13.6$ eV and $\varepsilon = 2.408$ for nuclei with $Z < 60$. The other quantities used for the calculation of α half-lives are the quadrupole (β_2) and hexadecapole (β_4) deformation values of both the parent and the daughter nuclei. In this paper, we have considered only the odd-even and the odd-odd nuclei. For those nuclei, the experimental deformation values are not available, and hence, the theoretical values taken from Ref. [64] are used.

The possibility of the formation of the superheavy nucleus $^{299}119$ was brought out by Zagrebaev *et al.* [14] where they studied the decay properties, namely, α, β, and spontaneous fission. This gave us the inspiration to carry out an extensive study on the α half-lives and the spontaneous fission half-lives of all the possible isotopes of $Z = 119$, beginning with $^{274}119$ (the first isotope found in Ref. [62]). The calculations were carried out for the rest of the isotopes, and the entire study is given in Figs. 1–10 where $\log_{10}(T_{1/2})$ is plotted against the mass number of the corresponding parent nuclei. The α-decay half-lives of these isotopes, calculated by using the CPPMDN formalism [which includes the quadrupole (β_2) and hexadecapole (β_4) deformation values of both the parent and the daughter nuclei], are depicted as solid red lines (with open triangles) in these plots. Here, we would like to mention that, in the case of the nuclei of ^{278}Rg, $T_\alpha^{\exp} = 4.200 \times 10^{-3} s$ and $T_\alpha^{\text{calc.}} = 1.628 \times 10^{-3}$ s; in the case of ^{275}Mt, $T_\alpha^{\exp} = 9.700 \times 10^{-3} s$ and $T_\alpha^{\text{calc.}} = 7.885 \times 10^{-3}$ s; in the case of ^{255}Es, $T_\alpha^{\exp} = 2.751 \times 10^5 s$ and $T_\alpha^{\text{calc.}} = 5.799 \times 10^5$s, which shows the close agreement between the experimental α half-lives [65] and the α half-lives computed within the CPPMDN. Our earlier formalism, the CPPM [which excluded the quadrupole (β_2) and hexadecapole (β_4) deformation values of both the parent and the daughter nuclei] have also been used for the α half-life calculations and are represented as solid pink lines (with open circles). From all the plots, it is evident that the inclusion of the deformation values decreases the α half-lives. The α half-life calculations are also performed by using the well-established Viola-Seborg semiempirical (VSS) relationship, given as

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

Instead of using the original set of constants by Viola and Seaborg [27], more recent values determined in an adjustment that takes account of new data for even-even nuclei by Sobiczewski *et al.* [66] are used. The half-life is in seconds, the Q value is in MeV, and Z is the atomic number of the parent nucleus. The constants $a = 1.66175$, $b = -8.5166$, $c = -0.20228$, $d = -33.9069$, and the value of $h_{\log}$ is taken as

$$\begin{aligned} h_{\log} &= 0 && \text{for} \quad Z, N \ \text{even}, \\ h_{\log} &= 0.772 && \text{for} \ Z = \text{odd}, \quad N = \text{even}, \\ h_{\log} &= 1.066 && \text{for} \ Z = \text{even}, \quad N = \text{odd}, \\ h_{\log} &= 1.114 && \text{for} \quad Z, N \ \text{odd}, \end{aligned}$$

so as to incorporate the odd-even effects. The quantities a, b, c, and d are adjustable parameters, and the quantity $h_{\log}$ represents the hindrances associated with odd proton and odd neutron numbers as given by Viola-Seaborg [27]. The computed VSS values are represented as solid blue lines (with solid triangle) in the figures.

In the present paper, we also have performed the calculation of spontaneous fission (SF) half-lives for all the isotopes and their decay products. This is performed so as to identify the mode of decay of the isotopes under study. Those isotopes with smaller α-decay half-lives than spontaneous fission half-lives survive fission, and such isotopes can, hence, be detected through α decay in the laboratory. The semiempirical relation given by Xu *et al.* [67] has been used for the calculation of spontaneous fission half-lives, and the relation is given as

$$T_{1/2} = \exp\left\{2\pi\left[C_0 + C_1A + C_2Z^2 + C_3Z^4 + C_4(N-Z)^2 - \left(0.13323\frac{Z^2}{A^{1/3}} - 11.64\right)\right]\right\}, \quad (17)$$

where the constants are $C_0 = -195.09227$, $C_1 = 3.10156$, $C_2 = -0.04386$, $C_3 = 1.4030 \times 10^{-6}$, and $C_4 = -0.03199$. Equation (17) was originally made to fit the even-even nuclei. But in this study, we have considered only the odd-Z (both odd-even and odd-odd) nuclei. So, instead of taking spontaneous fission half-life T_{sf} directly, we have taken the average of fission half-life T_{sf}^{av} of the corresponding neighboring even-even nuclei as the case may be. The T_{sf}^{av} of two neighboring even-even nuclei have been considered while dealing with the odd-even nuclei and the T_{sf}^{av} of four neighboring even-even nuclei were taken in the case of odd-odd nuclei. The spontaneous fission half-lives are denoted as black solid lines (with solid squares) in the plots. Here, it is to be noted that, in the case of the nuclei of ^{259}Md, $T_{sf}^{\exp} = 5.760 \times 10^3 s$ and $T_{sf}^{av} = 9.044 \times 10^3$ s; in the case of ^{257}Es, $T_{sf}^{\exp} = 7.484 \times 10^5 s$ and $T_{sf}^{av} = 1.988 \times 10^5$s; in the case of ^{262}Db, $T_{sf}^{\exp} = 11.550\, s$ and $T_{sf}^{av} = 6.9415$ s, which shows good agreement between experimental and computed average spontaneous fission half-lives. The experimental spontaneous fission values are taken from Ref. [65]. The T_{sf}^{av} values calculated by using the semiempirical relation given by Xu *et al.* are compared with the α-decay half-lives evaluated by using our CPPMDN formalism, and thereby, we have predicted the mode of decay of about 40 isotopes of $Z = 119$.

Figure 1 gives the plot for $^{274-277}$119 superheavy nuclei. We could see that both ^{274}119 and ^{275}119 isotopes and their decay products do not survive fission. But the isotopes of ^{276,277}119 survive fission, and our study predicts a one α chain from these isotopes. In Fig. 2, we have plotted the $\log_{10}(T_{1/2})$ versus mass number for the nuclei of $^{278-281}$119. From the comparison of α half-lives with corresponding spontaneous fission half-lives, we could predict two α chains for ^{278,279}119 and three α chains from ^{280,281}119. The plots for $^{282-285}$119, $^{286-289}$119, and $^{290-293}$119 are shown in Figs. 3–5, respectively. Even though all these isotopes survive fission, our calculations show that the α half-lives for those isotopes of $Z = 119$ in the range of $282 \leqslant A \leqslant 291$ are below the millisecond region (e.g., $T_{1/2}^{\alpha} = 1.175 \times 10^{-8}$s for ^{282}119 and $T_{1/2}^{\alpha} = 8.785 \times 10^{-7}$s for ^{284}119) and, hence, cannot be detected through α decay. But the isotopes of ^{292}119 and ^{293}119, given in Figs. 5(c) and 5(d) for which the decay chain studies are also given in Table I, survive fission, and our study predicts six α chains from each of the nuclei. The study on the isotopes of $^{294-297}$119 and $^{298-301}$119 are given in Figs. 6 and 7, respectively. From these figures, it is clear that all those isotopes survive fission, and α decays can be observed from them. Within the CPPMDN, we have predicted six consistent α-decay chains from ^{294,295}119, five consistent α-decay chains from ^{296}119, four consistent α-decay chains from ^{297}119, and three consistent α-decay chains from ^{298,299}119. Our study on ^{299}119, depicted in Fig. 7(b), reveals that three consistent α-decay chains can be observed from that isotope. The experimental study on the same isotope performed by Zagrebaev *et al.* [14] predicts the possibility of only two α chains from it. The isotopes of ^{300,301}119 also survive fission, and there is a possibility of finding two α chains from them as per our predictions.

In the case of $^{302-305}$119, shown in Fig. 8, two α chains are observed for ^{302,303}119, and only one α chain is observed for ^{304,305}119. From Fig. 9, which gives the plot for the nuclei of $^{306-309}$119, it is clear that, from the isotopes of $^{306-308}$119, only one α chain can be seen, and the isotope ^{309}119 does not survive fission. Figure 10 gives the plot for

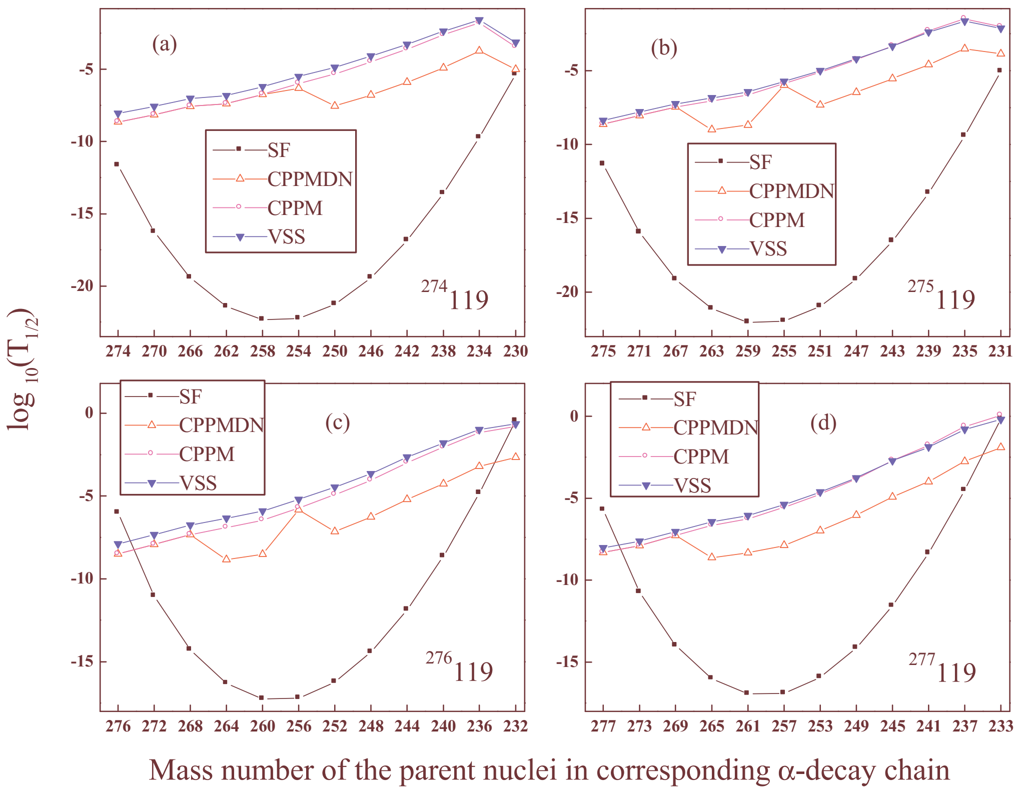

FIG. 1. (Color online) The comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for the isotopes $^{274-277}119$ and their decay products.

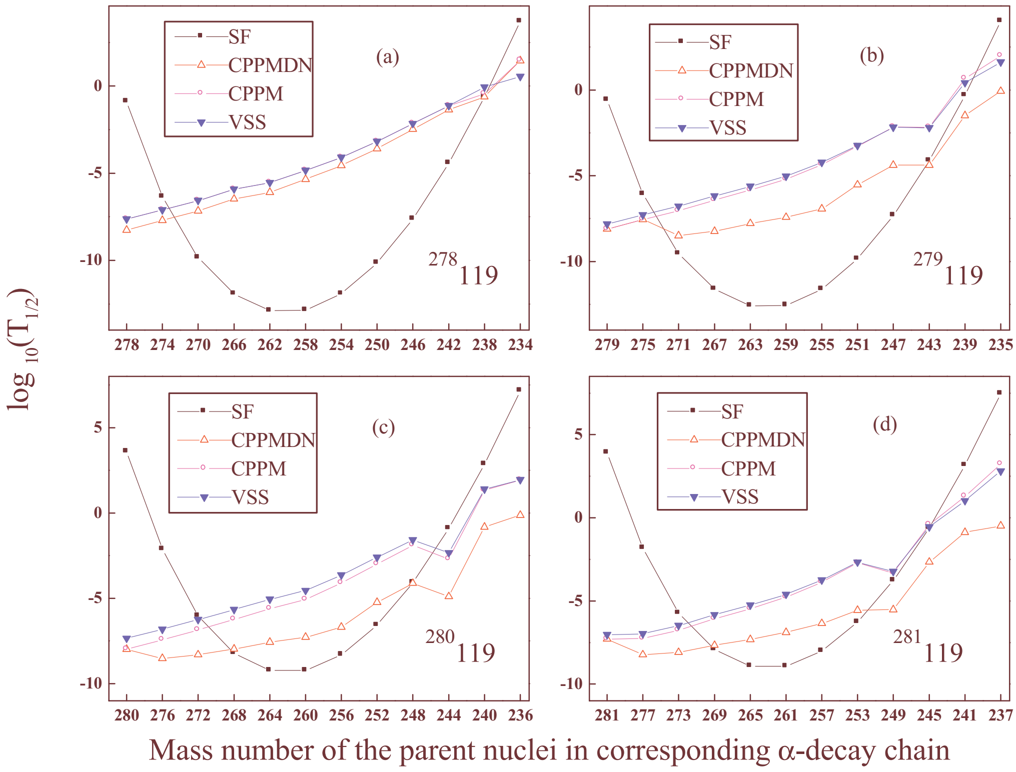

FIG. 2. (Color online) The comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for the isotopes $^{278-281}119$ and their decay products.

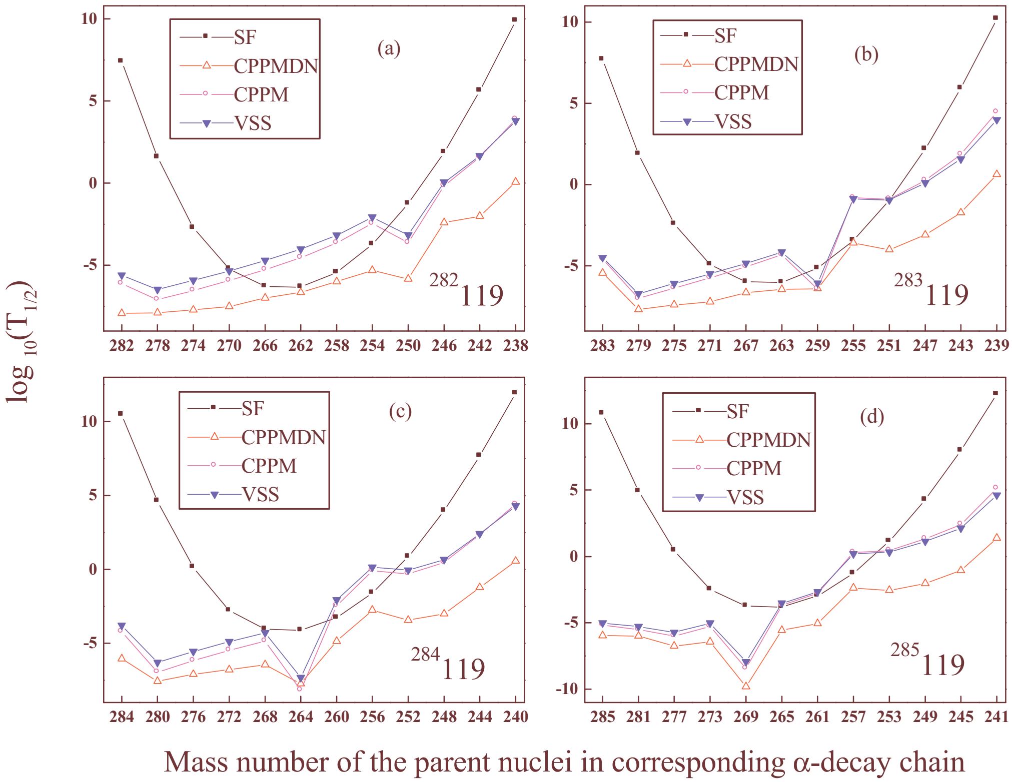

FIG. 3. (Color online) The comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for the isotopes $^{282-285}119$ and their decay products.

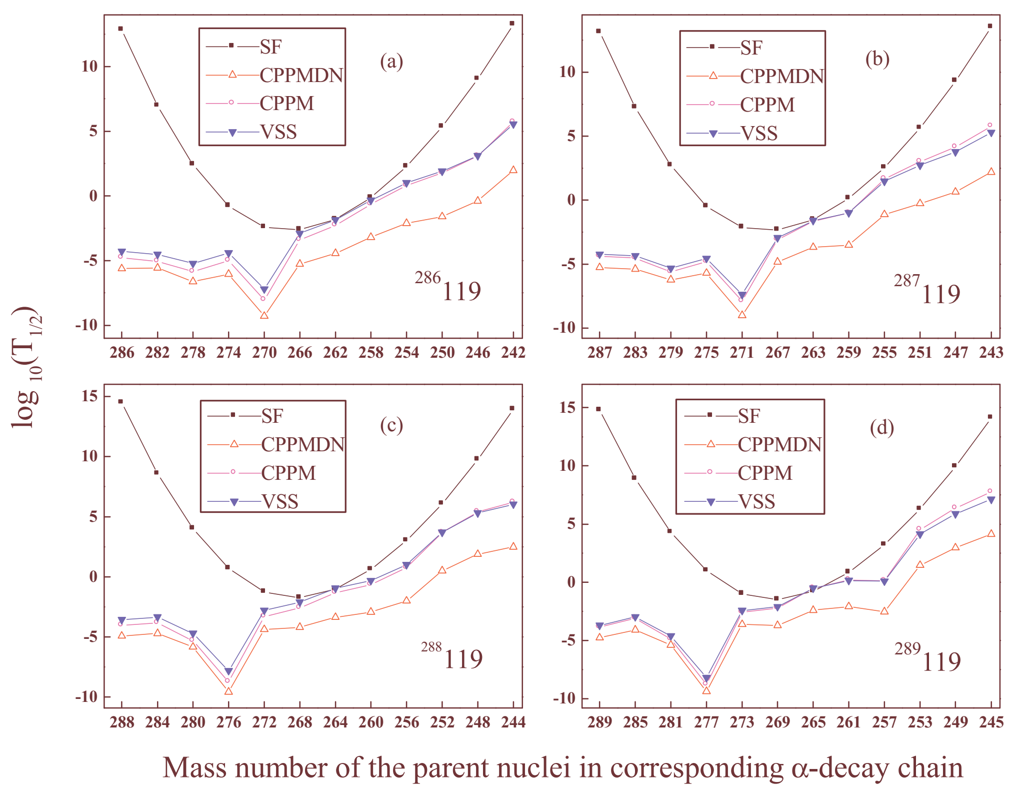

FIG. 4. (Color online) The comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for the isotopes $^{286-289}119$ and their decay products.

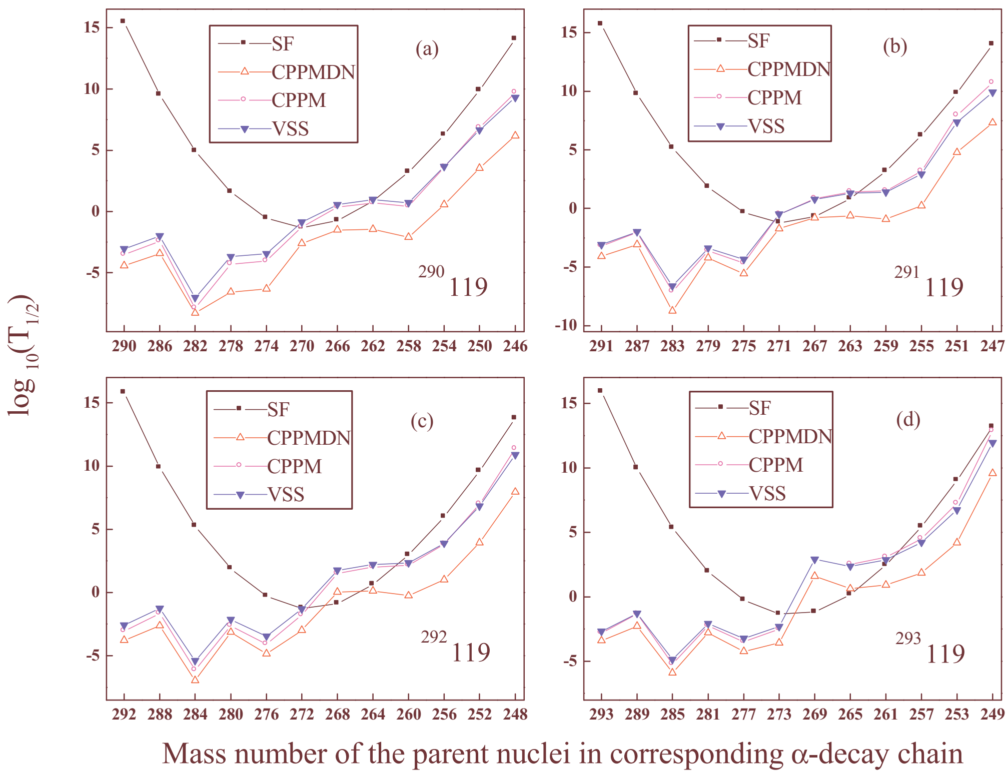

FIG. 5. (Color online) The comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for the isotopes $^{290-293}119$ and their decay products.

the isotopes of $^{310-313}119$, and none of them survive fission and, hence, completely undergo spontaneous fission. Thus, through our entire study, we would like to emphasize the fact that the isotopes of $Z = 119$ above $A \geqslant 309$ and the isotopes below $A \leqslant 275$ do not survive fission, and thus, the α decay is restricted within the range of $276 \leqslant A \leqslant 308$. From our entire study, we conclude and predict that the nuclei of $^{292-295}119$, $^{296}119$, $^{297}119$, and $^{298,299}119$ can be synthesized and can be detected experimentally as they consistently give six, five, four, and three α chains, respectively. Relatively long half-lives predicted for many of these unknown nuclei are sufficient to detect them if synthesized in a laboratory.

TABLE I. The α-decay half-lives and spontaneous fission half-lives of $^{292,293}119$ and their decay products. The mode of decay is predicted by comparing the α-decay half-lives with the spontaneous fission half-lives. The α half-life calculations are performed for zero angular momentum transfers.

Parent nuclei	Q_α(cal) (MeV)	T_{SF}^{av}(s)	$T_{1/2}^{\alpha}$(s)			Mode of decay
			CPPMDN	CPPM	VSS	
$^{292}119$	12.16	6.575×10^{15}	1.634×10^{-4}	8.830×10^{-4}	2.574×10^{-3}	$\alpha 1$
$^{288}117$	11.34	7.395×10^{9}	2.388×10^{-3}	2.218×10^{-2}	5.449×10^{-2}	$\alpha 2$
$^{284}115$	12.99	1.804×10^{5}	1.070×10^{-7}	7.118×10^{-7}	3.969×10^{-6}	$\alpha 3$
$^{280}113$	11.22	7.832×10^{1}	7.131×10^{-4}	2.290×10^{-3}	7.295×10^{-3}	$\alpha 4$
$^{276}111$	11.54	5.148×10^{-1}	1.378×10^{-5}	8.250×10^{-5}	3.513×10^{-4}	$\alpha 5$
^{272}Mt	10.40	5.440×10^{-2}	1.042×10^{-3}	1.651×10^{-2}	4.879×10^{-2}	$\alpha 6$
^{268}Bh	9.08	1.295×10^{-1}	1.0574	3.243×10^{1}	5.676×10^{1}	SF
$^{293}119$	12.05	8.164×10^{15}	3.899×10^{-4}	1.567×10^{-3}	2.070×10^{-3}	$\alpha 1$
$^{289}117$	11.21	8.962×10^{9}	5.134×10^{-3}	4.698×10^{-2}	5.168×10^{-2}	$\alpha 2$
$^{285}115$	10.74	2.132×10^{5}	1.280×10^{-6}	6.151×10^{-6}	1.370×10^{-5}	$\alpha 3$
$^{281}113$	12.45	8.988×10^{1}	1.635×10^{-3}	5.742×10^{-3}	8.066×10^{-3}	$\alpha 4$
$^{277}111$	11.23	5.580×10^{-1}	5.652×10^{-5}	3.287×10^{-4}	5.942×10^{-4}	$\alpha 5$
^{273}Mt	10.88	4.632×10^{-2}	2.646×10^{-4}	3.106×10^{-3}	4.891×10^{-3}	$\alpha 6$
^{269}Bh	8.89	6.328×10^{-2}	3.963×10^{1}	1.221×10^{3}	7.805×10^{2}	SF
^{265}Db	8.55	1.4572	4.2739	3.324×10^{2}	2.331×10^{2}	SF

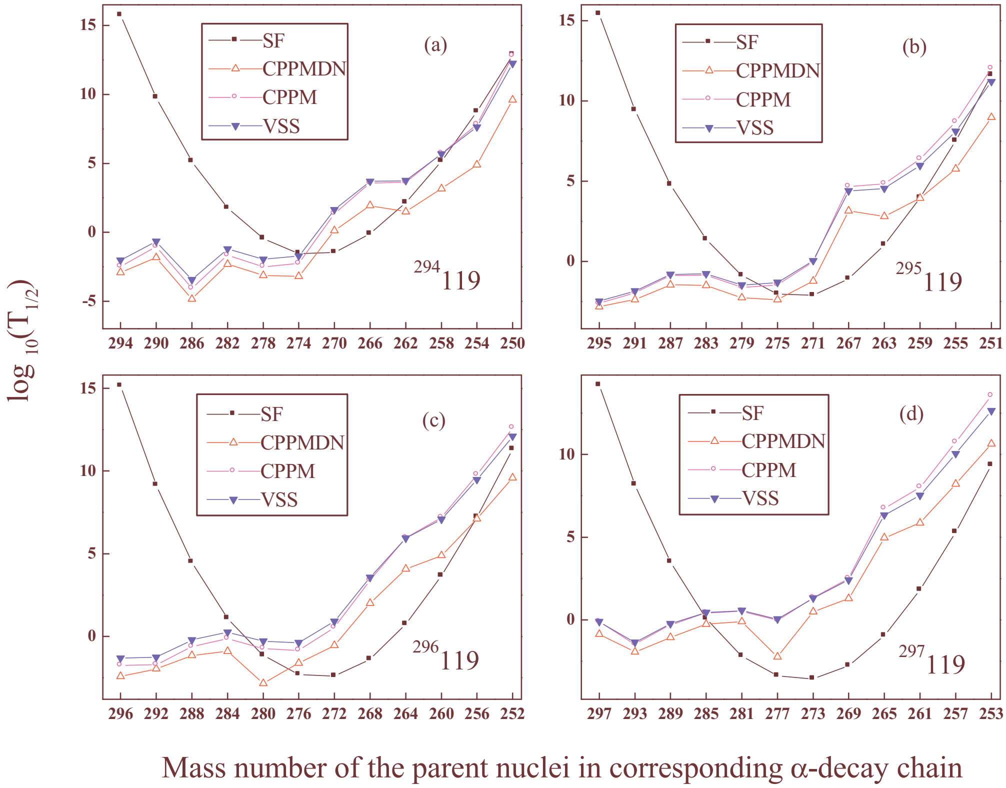

FIG. 6. (Color online) The comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for the isotopes $^{294-297}119$ and their decay products.

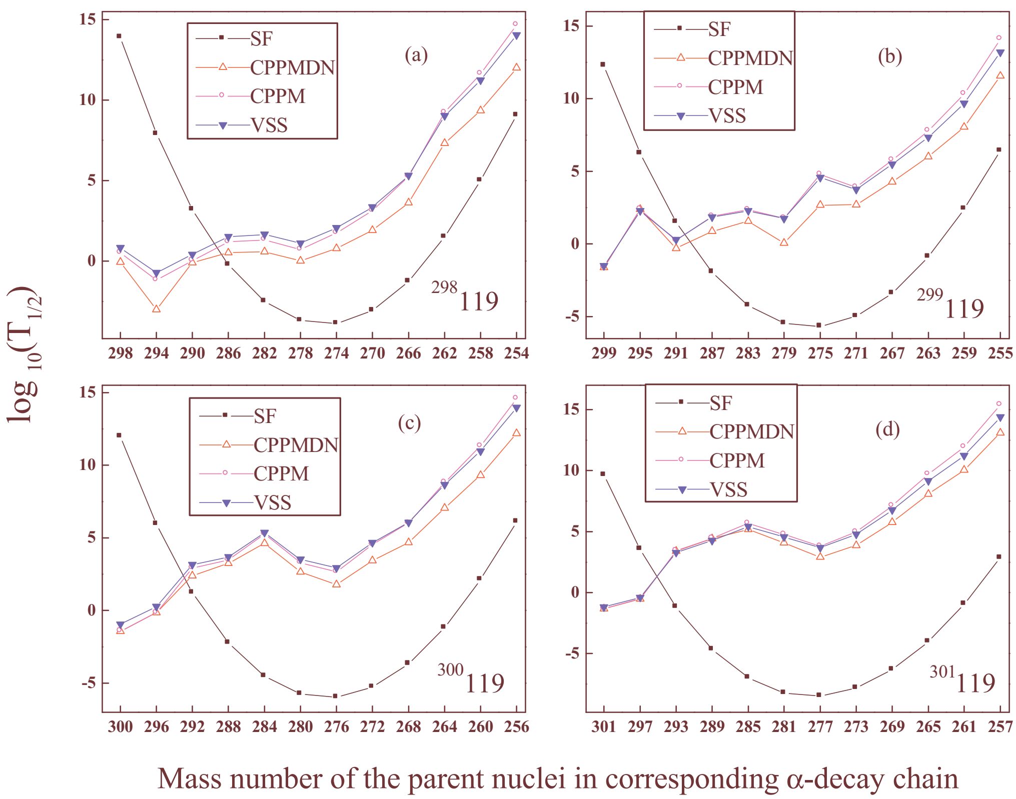

FIG. 7. (Color online) The comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for the isotopes $^{298-301}119$ and their decay products.

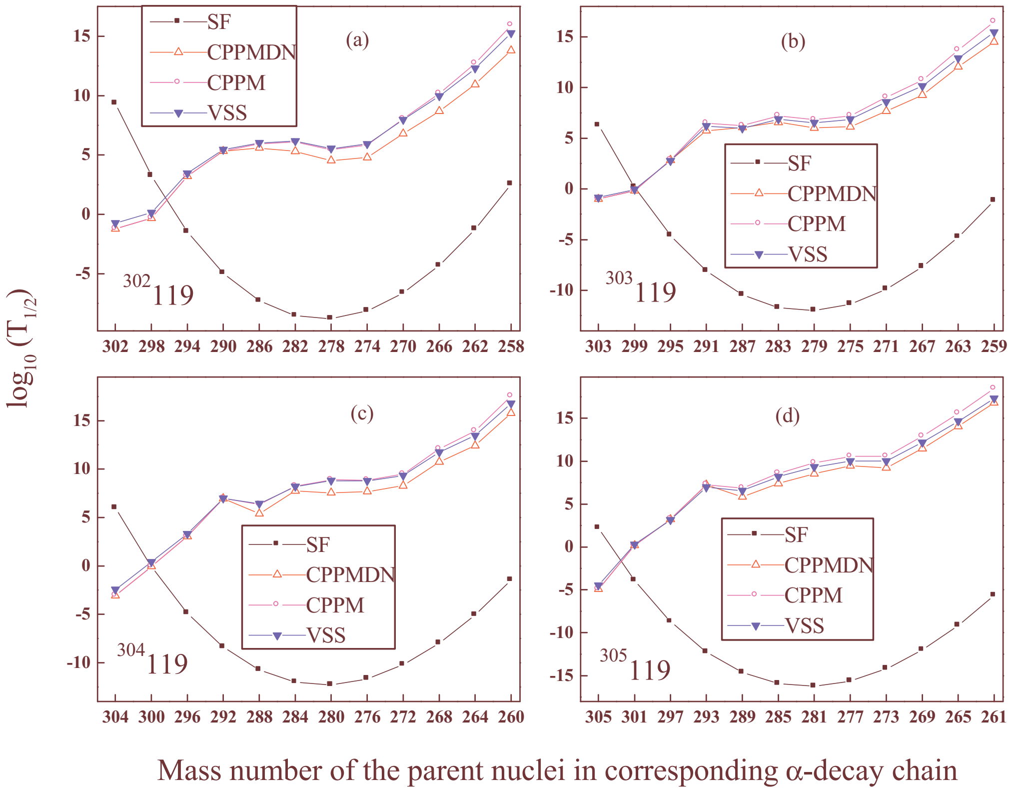

FIG. 8. (Color online) The comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for the isotopes $^{302\text{–}305}119$ and their decay products.

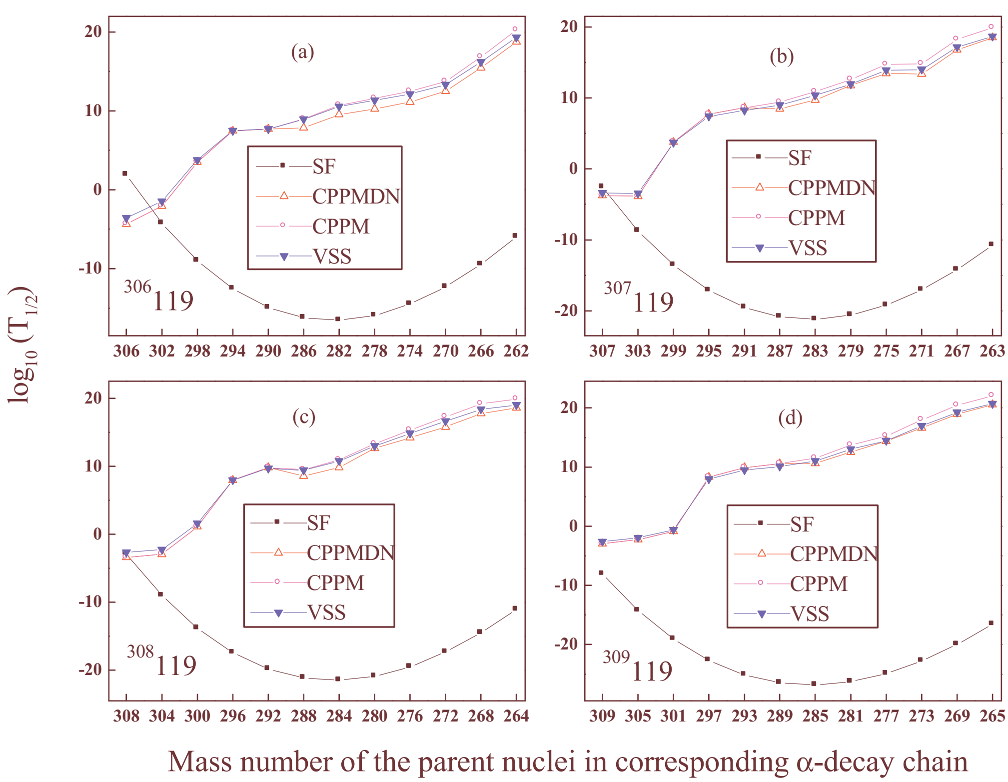

FIG. 9. (Color online) The comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for the isotopes $^{306\text{–}309}119$ and their decay products.

TABLE II. The α-decay half-lives and spontaneous fission half-lives of $^{294-296}119$ and their decay products. The mode of decay is predicted by comparing the α-decay half-lives with the spontaneous fission half-lives. The α half-life calculations are performed for zero angular momentum transfers.

Parent nuclei	Q_α(cal) (MeV)	T_{SF}^{av} (s)	$T_{1/2}^{\alpha}$(s)			Mode of decay
			CPPMDN	CPPM	VSS	
$^{294}119$	11.91	5.372×10^{15}	1.215×10^{-3}	3.327×10^{-3}	9.496×10^{-3}	$\alpha 1$
$^{290}117$	11.10	5.811×10^{9}	1.445×10^{-2}	8.909×10^{-2}	2.136×10^{-1}	$\alpha 2$
$^{286}115$	10.48	1.363×10^{5}	1.408×10^{-5}	8.707×10^{-5}	3.620×10^{-4}	$\alpha 3$
$^{282}113$	12.30	5.668×10^{1}	4.884×10^{-3}	2.133×10^{-2}	6.206×10^{-2}	$\alpha 4$
$^{278}111$	10.77	3.446×10^{-1}	7.335×10^{-4}	3.187×10^{-3}	1.108×10^{-2}	$\alpha 5$
^{274}Mt	10.56	2.791×10^{-2}	6.351×10^{-4}	5.571×10^{-3}	1.911×10^{-2}	$\alpha 6$
^{270}Bh	9.35	3.543×10^{-2}	1.3099	2.218×10^{1}	4.272×10^{1}	SF
^{266}Db	8.25	7.694×10^{-1}	8.614×10^{1}	3.693×10^{3}	4.970×10^{3}	SF
$^{295}119$	10.99	2.579×10^{15}	1.502×10^{-3}	2.410×10^{-3}	3.317×10^{-3}	$\alpha 1$
$^{291}117$	11.95	2.659×10^{9}	4.172×10^{-3}	1.086×10^{-2}	1.421×10^{-2}	$\alpha 2$
$^{287}115$	11.36	5.939×10^{4}	3.462×10^{-2}	1.306×10^{-1}	1.514×10^{-1}	$\alpha 3$
$^{283}113$	10.65	2.348×10^{1}	3.209×10^{-2}	1.383×10^{-1}	1.660×10^{-1}	$\alpha 4$
$^{279}111$	10.51	1.351×10^{-1}	5.386×10^{-3}	2.386×10^{-2}	3.372×10^{-2}	$\alpha 5$
^{275}Mt	10.17	9.492×10^{-3}	4.107×10^{-3}	3.420×10^{-2}	4.832×10^{-2}	$\alpha 6$
^{271}Bh	9.56	7.582×10^{-3}	5.983×10^{-2}	9.673×10^{-1}	1.0968	SF
^{267}Db	7.95	8.159×10^{-2}	1.416×10^{3}	4.676×10^{4}	2.481×10^{4}	SF
$^{296}119$	11.53	1.368×10^{15}	3.738×10^{-3}	1.761×10^{-2}	4.806×10^{-2}	$\alpha 1$
$^{292}117$	11.65	1.406×10^{9}	1.074×10^{-2}	1.902×10^{-2}	5.449×10^{-2}	$\alpha 2$
$^{288}115$	11.06	3.129×10^{4}	7.031×10^{-2}	2.389×10^{-1}	6.043×10^{-1}	$\alpha 3$
$^{284}113$	10.30	1.234×10^{1}	1.265×10^{-1}	7.427×10^{-1}	1.8024	$\alpha 4$
$^{280}111$	10.04	7.076×10^{-2}	1.423×10^{-3}	1.840×10^{-1}	5.107×10^{-1}	$\alpha 5$
^{276}Mt	9.85	4.952×10^{-3}	2.425×10^{-2}	1.415×10^{-1}	4.098×10^{-1}	SF
^{272}Bh	9.36	3.926×10^{-3}	2.839×10^{-1}	3.4306	8.0707	SF

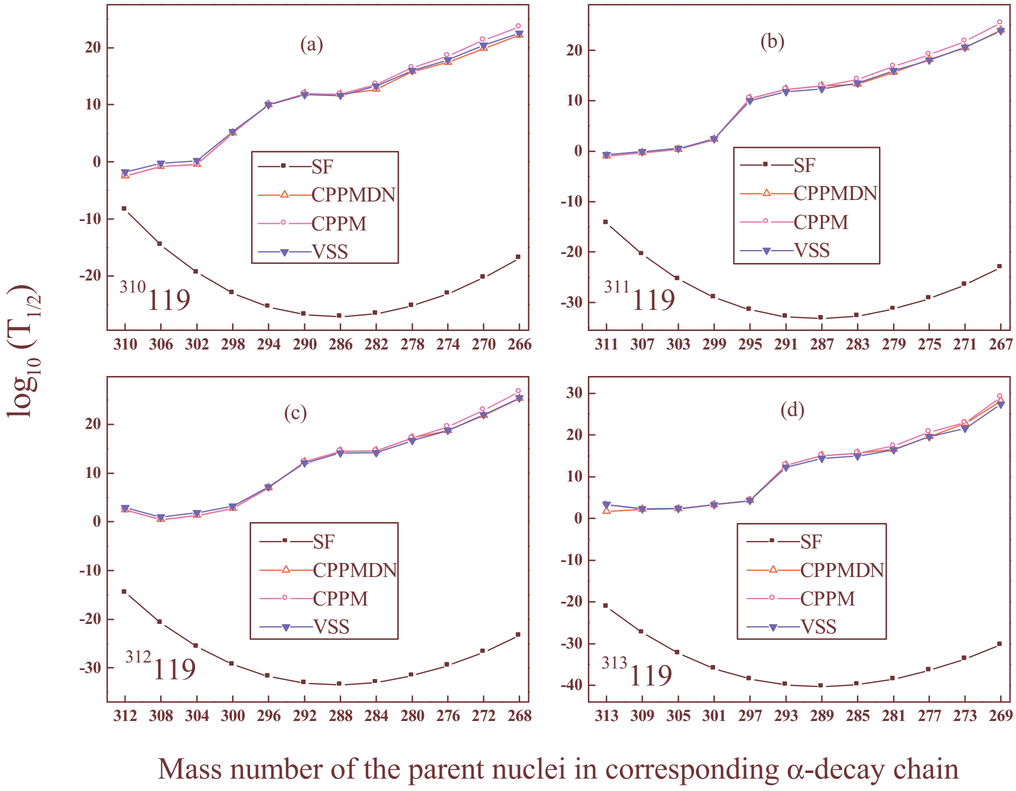

FIG. 10. (Color online) The comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for the isotopes $^{310-313}119$ and their decay products.

TABLE III. The α-decay half-lives and spontaneous fission half-lives of $^{297-299}119$ and their decay products. The mode of decay is predicted by comparing the α-decay half-lives with the spontaneous fission half-lives. The α half-life calculations are performed for zero angular momentum transfers.

Parent nuclei	Q_α(cal) (MeV)	T_{SF}^{av} (s)	$T_{1/2}^{\alpha}$(s)			Mode of decay
			CPPMDN	CPPM	VSS	
$^{297}119$	11.35	1.573×10^{14}	1.341×10^{-1}	7.728×10^{-1}	7.686×10^{-1}	$\alpha 1$
$^{293}117$	11.73	1.524×10^{8}	1.147×10^{-2}	3.360×10^{-2}	4.357×10^{-2}	$\alpha 2$
$^{289}115$	10.65	3.196×10^{3}	8.647×10^{-2}	5.030×10^{-1}	5.692×10^{-1}	$\alpha 3$
$^{285}113$	10.08	1.1861	5.381×10^{-1}	2.6168	2.7397	$\alpha 4$
$^{281}111$	9.69	6.390×10^{-3}	7.648×10^{-1}	3.3838	3.6017	SF
^{277}Mt	9.56	4.123×10^{-4}	5.718×10^{-3}	9.332×10^{-1}	1.1105	SF
$^{298}119$	11.39	7.959×10^{13}	8.682×10^{-1}	3.3292	6.8373	$\alpha 1$
$^{294}117$	12.20	7.705×10^{7}	9.638×10^{-4}	6.773×10^{-2}	1.903×10^{-1}	$\alpha 2$
$^{290}115$	10.35	1.615×10^{3}	8.083×10^{-1}	1.0734	2.6221	$\alpha 3$
$^{286}113$	9.74	5.989×10^{-1}	3.3346	1.577×10^{1}	3.319×10^{1}	SF
$^{282}111$	9.43	3.224×10^{-3}	3.9187	2.131×10^{1}	4.538×10^{1}	SF
$^{299}119$	11.54	1.854×10^{12}	2.389×10^{-2}	2.389×10^{-2}	3.222×10^{-2}	$\alpha 1$
$^{295}117$	12.40	1.687×10^{6}	2.443×10^{2}	2.443×10^{2}	1.865×10^{2}	$\alpha 2$
$^{291}115$	10.06	3.323×10^{1}	4.867×10^{-1}	1.7714	1.9679	$\alpha 3$
$^{287}113$	9.39	1.158×10^{-2}	7.4774	8.177×10^{1}	7.240×10^{1}	SF
$^{283}111$	9.02	5.823×10^{-5}	3.671×10^{1}	2.301×10^{2}	1.958×10^{2}	SF

As none of the isotopes of $Z = 119$ have been discovered yet, we hope these observations provide a new guide for experimentalists.

The predictions on the mode of decay of those superheavy elements that may be experimentally feasible and that may pave the way for future experiments are given separately in Tables I–III. The predictions on $^{292}119$ and $^{293}119$ and their decay products are given in Table I. In Tables II and III, we have predicted the decay modes of $^{294-296}119$ and $^{297-299}119$ and their decay products, respectively. The considered isotopes and their corresponding α-decay chains are given in column 1. The Q values for the corresponding α decays are given in column 2. In column 3, we have given the average spontaneous fission half-lives computed by using the phenomenological formula of Xu *et al.* [67]. The calculations of the α-decay half-lives performed within the CPPMDN formalism (with the ground-state deformation values of the both parent and the daughter nuclei) are given in column 4, and those calculated by using the CPPM formalism (without the ground-state deformation values of the both parent and the daughter nuclei) are given in column 5. The half-life values computed by using the VSS systematic are given in column 6, and in column 7, the predicted modes of decays of the isotopes are given. The comparison of the values, calculated by using both our formalisms, matches well with the VSS values in their order.

We would like to mention that the authors of Ref. [67] have shown that the predicted T_{sf} values of even-even nuclei may deviate from the experimental values by about 3 orders of magnitude (see, e.g., the nucleus of $^{284}112$), and the deviation still strongly increases by the effect of the odd nucleon (odd-A and odd-odd nuclei). In the papers on α-decay chains of element $Z = 117$, Sobiczewski [68], and Oganessian *et al.* [69] have shown that the addition of one or two nucleons will increase T_{sf} by roughly 1 or 2 orders of magnitude. The above-mentioned facts strongly change the relation between the calculated α and the spontaneous fission half-lives and may significantly change the results given in the last columns of Table I–III.

We would like to throw some light on the fact that our paper on the α decay of $Z = 119$ gives a comparison of α-decay half-lives and spontaneous fission half-lives, which helps in the prediction of the mode of decay of a vast range of isotopes in the range of $274 \leqslant A \leqslant 313$.

IV. CONCLUSION

The Coulomb and proximity potential calculations for the α decays of the yet-to-be-discovered superheavy element $Z = 119$ in the mass range of $A = 274$–313 (odd-even and odd-odd types of nuclei) have been performed within the CPPMDN. As the reliability and applicability of our model have been proved earlier through the α-decay studies on $Z = 115$ and $Z = 117$, here, we have confidently carried out the calculations on the α half-lives and the spontaneous fission half-lives of 40 isotopes of $Z = 119$. By using our study, we try to highlight the fact that those isotopes of $Z = 119$, above $A \geqslant 309$ and below $A \leqslant 275$, do not survive fission, and thus, the α decay is restricted within the range of $276 \leqslant A \leqslant 308$. We have predicted a one α chain from $^{276,277,304-308}119$, two α chains from $^{278,279,300-303}119$, three α chains from $^{280,281,298,299}119$, five α chains from $^{296}119$, four α chains from $^{297}119$, and six α chains from $^{292-295}119$ isotopes. The predictions for $^{292-295}119$, $^{296}119$, $^{297}119$, and $^{298,299}119$ may pave the way for the upcoming experiments as they consistently show six, five, four, and three α-decay chains. We, thus, hope our theoretical search on the α-decay properties of the yet-to-be-discovered SH element $Z = 119$ delivers new challenges for experimentalists.

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