NEW PREDICTIONS ON ALPHA DECAY HALF-LIVES OF SUPERHEAVY NUCLEI

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We systematically examine the alpha decay half-lives of 80 superheavy nuclei (SHN) with $104 \leq Z \leq 118$ employing the new analytical formula, which is obtained using the semi-classical Wentzel–Kramers–Brillouin (WKB) approximation within the framework of the alpha cluster model for the modified harmonic oscillator and spherical Coulomb potentials. We develop an empirical formula for the depth of the nuclear potential that satisfactorily describes the experimental data, and compare our results with the universal decay law (UDL), Royer formula, and the effective liquid drop model (ELDM) described in the literature. Relying on our model, which successfully explains the alpha decay half-lives of the synthesized superheavy nuclei, we predict the alpha decay half-lives of 101 superheavy nuclei with $104 \leq Z \leq 120$, whose experimental alpha decay half-lives are unknown, and compare the results with UDL, Royer, and ELDM models. The variation of the alpha decay half-lives of these models as a function of the neutron number exhibits the shell closure effect at $N = 178$ and $N = 184$.

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1. Introduction

The discovery of the superheavy elements (SHEs) with $Z \geq 104$ is one of the hot topics in nuclear physics. Intensive studies are carried out on the synthesis and decay properties of the isotopes of SHE, see Refs. [1–4] and references therein. The SHEs have been successfully synthesized by fusion-evaporation reaction of the double magic ^{48}Ca ions with actinide targets such as ^{237}Np, ^{243}Am, and ^{249}Bk nuclei [5–9]. The alpha decay chains of the produced SHEs have valuable information to understand the nuclear structure stability in the region of superheavy nuclei [10, 11]. Parkhomenko *et al.* [12] studied theoretically α-decay chains of ^{271}110 nuclei within a macroscopic–microscopic approach. In Ref. [13], α and heavier cluster decay half-lives and branching ratios have been examined from the parent $Z > 104$

superheavy nuclei. Some α decay, cluster decay, and spontaneous fission efforts have also been carried out for heavy and superheavy nuclei [14–18]. In another study, Poenaru *et al.* [20–22] have shown that the best dynamical trajectory during the deformation toward fission of some superheavy nuclei is a linearly increasing radius of the light fragment.

The shell structure in nucleus has major importance in understanding the nuclear structure stability. It is well known that the nuclei with proton or neutron numbers of 2, 8, 20, 28, 50, 82, and 126 have the large discontinuities in proton and neutron separation energies, high first excitation energies, and small total density distributions, which are important evidence of the shell structure in nucleus [23]. These observations in the nuclei can be explained using the shell model. There are lots of theoretical models to predict next shell numbers in the nuclei [23]. Sobiczewski *et al.* [24] predicted magic numbers $Z = 114$ and $N = 184$ using the single-particle model in the Woods–Saxon potential with spin-orbit term. Nilsson *et al.* [25] predicted the shell structure around $Z = 114$ and $N = 184$ using a deformed harmonic oscillator based on the deformable shell model. According to the self-consistent Skyrme–Hartree–Fock–Bogoliubov (HFB-SLy4) model calculation, $N = 184$ is the magic number [26]. The Skyrme–Hartree–Fock method with a density-independent contact pairing interaction shows that the $Z = 126$ and $N = 184$ are doubly magic superheavy elements [27]. Rutz *et al.* [28] investigated shell structure of superheavy nuclei within the framework of the relativistic and nonrelativistic nuclear mean-field models with various parameterizations and found double magic numbers as ($Z = 114$, $N = 184$), ($Z = 120$, $N = 172$), and ($Z = 126$, $N = 184$).

The dominant decay mode of superheavy nuclei is the alpha decay which plays an important role in understanding the shell structure properties of superheavy nuclei. Many efforts based on empirical or semi-empirical models have been made to develop a general extension of the Geiger–Nuttall law [29]. Some of the alpha decay half-life formulas that is obtained by using empirical or semi-empirical models are: Gamow [30], Viola–Seaborg relation [31] with the readjusted parameters [32], alpha cluster model [33, 34], the analytical superasymmetric fission (ASAF) model [35, 36], the semiempirical formula based on fission theory (SemFIS) [37] and modified version [38], Brown [39] and modified version [40], Royer [41] and extension [42], Horoi [43], unified formula [44], universal decay law (UDL) [45] and extended version [46, 47], one single line of the universal curve (UNIV) [48], general decay law [49] and improved version [50], Poenaru [51].

In most cases, analytical formulas for the alpha decay calculations using the phenomenological and microscopic potentials cannot be obtained. The effective potential obtained by folding the densities of the alpha and daughter nuclei in terms of the M3Y effective interaction can be used to numerically calculate the alpha decay half-lives of superheavy nuclei within the framework of the semi-classical WKB approximation [52, 53]. Due to the high deformation of superheavy nuclei, the density of daughter nucleus must be deformed in order to obtain a more realistic effective potential in the explanation of alpha decay half-lives of superheavy nuclei [54–58]. In the literature, there are also some phenomenological potential models to calculate the alpha decay half-lives of the superheavy nuclei using semi-classical WKB approximation. Some of these phenomenological potentials are the Coulomb and Proximity Potential Model (CPPM) [59] and deformed version [60–63], the "cosh" geometry [64–67], the modified version of the Woods–Saxon potential (SW+SW3) [68].

We have recently shown that the alpha decay half-life depends not only on the geometry of the Coulomb potential, but also on the depth of the nuclear potential [69]. The Gamow penetrability factor, which is the dominant term in the calculation of the alpha decay half-lives, depends on inner and outer turning points. The inner turning point (r_2) is affected by the depth of the nuclear potential. As a result, in the alpha decay calculation, the nuclear potential depth which is important to describe the nuclear structure of the parent nucleus should be taken into account [33, 34]. In this paper, our aims are to systematically investigate the alpha decay half-lives of 80 superheavy nuclei in the range of $104 \leq Z \leq 118$ using our analytical alpha decay formula [69] to predict the alpha decay half-lives with $104 \leq Z \leq 120$ superheavy nuclei whose experimental alpha decay half-lives are unknown, and to compare our results with the universal decay law (UDL) [70], the empirical formula of Royer [41], and the effective liquid drop model (ELDM) [71]. In the next section, we define the effective potential between the alpha particle and daughter nucleus. Then we briefly explain how to get the analytical formula for the alpha decay half-life in terms of the semi-classical WKB approximation. In Sec. 3, we present numerical results and discuss them in detail with the literature. Finally, we give the conclusion in Sec. 4.

2. Theoretical framework

We have recently proposed the effective potential constituted of the spherical Coulomb and modified harmonic oscillator potentials which present the interaction between a point charge alpha particle and a spherical nucleus having a uniform charge distributed over Coulomb radius to describe the decay of alpha particles from heavy nuclei for the zero angular momentum transfer (favored alpha decay) as follows [69]

$$\begin{aligned} V_{\text{eff}}(r) &= C_0 - V_0 + (V_1 - C_1)r^2\,, \quad && r \leq r_2 \\ &= \frac{C_2}{r}\,, && r > r_2\,, \end{aligned} \tag{1}$$

where $C_0 = \frac{3Z_\alpha Z_\mathrm{d} e^2}{2R_\mathrm{C}}$, $C_1 = \frac{Z_\alpha Z_\mathrm{d} e^2}{2R_\mathrm{C}^3}$, and $C_2 = Z_\alpha Z_\mathrm{d} e^2$. The V_0 and V_1 are the depth and diffusivity of the modified harmonic oscillator potential, respectively. The Coulomb radius R_C is expressed as $R_\mathrm{C} = 1.07(A_\alpha^{1/3} + A_\mathrm{d}^{1/3})$ [83]. The Coulomb potential parameters Z_α, A_α and Z_d, A_d are the atomic and mass numbers of the alpha particle and daughter nucleus, respectively.

According to the cluster model [33, 34], the alpha particle is already preformed in the parent nucleus and orbiting around the daughter nucleus. Within the framework of the Bohr–Sommerfeld quantization condition, the alpha clustering effect can be taken into account with the Wildermuth rule [78] using the global quantum number $G = 2n + L$, where n and L are the radial node and angular momentum quantum numbers. The decay half-life formula can be analytically obtained employing the semi-classical WKB approach in terms of the Bohr–Sommerfeld quantization condition for the effective potential in equation (1) as in [69]

$$\log_{10} T_{1/2} = a + \frac{b}{\sqrt{Q_\alpha}}\,, \tag{2}$$

where a and b are the decay parameters as follows:

$$\begin{aligned} a &= \log_{10}\left(\frac{\pi\hbar \ln 2}{P}\frac{G+1}{Q_\alpha + V_0 - C_0}\right), \\ b &= 2C_2 \log_{10}(e)\sqrt{\frac{2\mu}{\hbar^2}}\left(\arccos\left(\sqrt{\frac{r_2}{r_3}}\right) - \sqrt{\frac{r_2}{r_3} - \left(\frac{r_2}{r_3}\right)^2}\right). \end{aligned} \tag{3}$$

We should emphasize that the alpha decay formula in equation (2), which is obtained using the basic principles of quantum mechanics, includes the spherical Coulomb potential and has only one degree of freedom which is the depth of the nuclear potential (V_0). In order to be consistent with the literature, $G = 22$ has been taken for the superheavy nuclei with neutron number of the parent nuclei $N > 126$ [33, 34]. The preformation factor P has values in the range of $P = 0.004$–1 in the literature [79]. Thus, in all calculations, we use the values of the preformation factor as $P = 1, 0.4$ and 0.35 for even–even, even–odd or odd–even, and odd–odd nuclei, respectively. These values are the best preformation factors which give minimum root-mean-square (r.m.s.) deviations. The reduced mass of the alpha–daughter binary system is given by $\mu = \frac{m_\alpha m_\mathrm{d}}{m_\alpha + m_\mathrm{d}} u$ and evaluated from Ref. [80]. Here, m_α and m_d are the mass of the alpha particle and the daughter nucleus, respectively. The atomic mass unit is $u = 931.494$ MeV$/c^2$. The inner and outer turning points r_2 and r_3 in Eq. (3) can be obtained using the equation of $Q_\alpha = V_\mathrm{eff}(r)$ as $r_2 = \sqrt{\frac{2\hbar^2}{\mu}\frac{(1+G)^2}{Q_\alpha + V_0 - C_0}}$ and $r_3 = \frac{C_2}{Q_\alpha}$. Q_α is the alpha decay energy and is equal to mass excess in energy unit between the parent nucleus and decay products [72]. The unit of alpha decay half-life is in seconds in Eq. (2). In the literature, there are lots of nuclear mass models such as Weizsäcker–Skyrme-4 (WS4) [73, 74], the finite-range droplet model (FRDM) [75], the Kourra–Tachibaba–Uno–Yamada (KTUY) formula [76], and Hartree–Fock–Bogoliubov mean field with the D1S Gogny force (GHFB) [77]. In calculations, we use the alpha decay energies obtained with the WS4 mass model in [71]. We also take some alpha decay energies from National Nuclear Data Center (NuDat 2.8) [82].

To compare our results with the empirical formulas in the literature, we have also calculated the alpha decay half-lives using the universal decay law (UDL) and Royer's formula. The UDL model is as follows:

$$\log_{10} T_{1/2} = a\sqrt{\frac{A}{Q_\alpha}}Z_\alpha Z_\mathrm{d} + b\left(AZ_\alpha Z_\mathrm{d}\left(A_\alpha^{1/3} + A_\mathrm{d}^{1/3}\right)\right)^{1/2} + c\,, \tag{4}$$

where $A = \frac{A_\alpha A_\mathrm{d}}{A_\alpha + A_\mathrm{d}}$ and the constants a, b, and c are taken as $a = 0.3949$, $b = -0.3693$, and $c = -23.7615$, respectively [70]. Royer has proposed a simple analytical formula and predicted the alpha decay half-lives of superheavy nuclei with atomic numbers in the range of $104 \leq Z \leq 118$ [41]. Royer's formula is as follows [41]:

$$\log_{10} T_{1/2} = a + bA^{1/6}\sqrt{Z} + \frac{cZ}{\sqrt{Q_\alpha}}\,, \tag{5}$$

where $a = -26.06$, $b = -1.114$, and $c = 1.5837$ are the decay constants. Z and A are the atomic and mass numbers of the parent nucleus, respectively.

3. Results and discussions

We have firstly investigated the alpha decay half-lives of 80 superheavy nuclei whose experimental data are known in the range of $104 \leq Z \leq 118$ using the alpha decay formula in equation (2). The unknown term in our formula is only the depth of the nuclear potential (V_0). Using the experimental half-lives $T_{1/2}^{\mathrm{Exp}}$ and alpha decay energies Q_α, we calculate the exact values of the V_0 parameter of all these daughter–alpha binary systems. The values of the nuclear potential depths are in the range of 172.58 MeV $\leq V_0 \leq 221.48$ MeV and do not have a linear distribution with respect to the atomic mass number A, neutron number N, and proton number Z of the parent nucleus. Then, we simply use the arithmetic average value of the depth of the nuclear potential as $V_0 = 189.90$ MeV. In order to get a quantitative analysis of alpha decay half-lives of superheavy nuclei, we have calculated r.m.s. deviations between experimental and theoretical alpha decay half-lives in decimal logarithms using the r.m.s. formula defined as [81]

$$\delta = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\log_{10} T_{i,1/2}^{\mathrm{Exp}} - \log_{10} T_{i,1/2}^{\mathrm{Theory}}\right)^2}\,, \tag{6}$$

where n indicates a number of the parent nuclei. Here, $T_{i,1/2}^{\mathrm{Exp}}$ and $T_{i,1/2}^{\mathrm{Theory}}$ are the experimental and theoretical alpha decay half-lives, respectively. Taking the depth of the nuclear potential as $V_0 = 189.90$ MeV, we find the r.m.s. deviation as $\delta = 0.52$. In order to further minimize the r.m.s. deviation, we have also searched for an empirical formula for the nuclear potential depth as a function of the mass, neutron, and proton numbers of the parent and daughter nuclei in order to find an optimum potential depth and found a formula which is depending on the daughter nuclei A_{d} as

$$V_0 = -0.48 A_{\mathrm{d}} + 319.72 \ \mathrm{MeV}\,. \tag{7}$$

By using the empirical formula in Eq. (7), we calculate the r.m.s. deviation of superheavy nuclei whose experimental data are known in the range of $104 \leq Z \leq 118$ presented in Table 1 for the alpha cluster model and find the r.m.s. deviation as $\delta = 0.44$ which is more accurate than the results of $V_0 = 189.90$ MeV. Then, we also calculate the r.m.s. deviations of alpha decay half-lives between the experimental data and theoretical results of the UDL, and Royer models, and find $\delta = 0.61$ and 0.59, respectively. The r.m.s. deviation of the ELDM model is 0.58 [71]. Therefore, the r.m.s. deviation in the results of the alpha cluster model is in good agreement with the UDL, Royer, and ELDM models. In Table 1, we satisfactorily describe alpha decay half-lives of the 80 superheavy nuclei using the alpha cluster model. The first four columns show the parent nuclei, alpha decay energies, experimental half-lives, and alpha cluster model, respectively. The fifth and sixth columns show the half-lives calculated using the universal decay law (UDL) and the formula developed by Royer [41, 70]. The last column is the half-lives obtained with the ELDM [71]. The alpha decay half-lives produced by Royer's formula and ELDM are very close to each other. In order to present the deviations between the experimental and theoretical half-lives, we take the decimal logarithm of the ratios of experimental and theoretical half-lives and plot *versus* atomic mass number A of the parent nuclei in figure 1. The black circle, red diamond, green up-triangle, and blue down-triangle show the present, UDL, Royer, and ELDM models, respectively. The deviations between the experimental and theoretical half-lives in most cases are within a factor of approximately three. The parameters of the UDL model should be readjusted to get more convenient results in figure 1.

In figure 2, we present a logarithmic comparison of experimental half-lives with the alpha cluster model results *versus* $Z/\sqrt{Q_\alpha}$. The black and red circles are the present theoretical results and experimental data, respectively. Although there is a Geiger–Nuttall plot for the isotopic chains of the nuclei, we cannot get a linear correlation between the alpha decay half-lives and $Z/\sqrt{Q_\alpha}$ parameter in the range of $104 \le Z \le 118$ (see figure 2 (a)). However, there is a linear correlation between $(\log_{10} T_{1/2}) - a$ and $\frac{b}{\sqrt{Q_\alpha}}$ in equation (2) for the 80 superheavy nuclei presented in figure 2 (b). As a result, it is clear that the alpha cluster model for the effective potential in equation (1) is a suitable tool to satisfactorily explain the experimental alpha decay half-lives of superheavy nuclei.

Table 1: Comparison of experimental and theoretical alpha decay half-lives of superheavy nuclei for $104 \le Z \le 118$ nuclei with the alpha cluster, UDL, Royer, and ELDM models. Experimental alpha decay half-lives and Q_α values are extracted from Ref. [71]. The unit of alpha decay half-life is in seconds.

Parent	Q_α [MeV]	$\log_{10} T_{1/2}^{\mathrm{Exp}}$	$\log_{10} T_{1/2}^{\mathrm{Present}}$	$\log_{10} T_{1/2}^{\mathrm{UDL}}$ [70]	$\log_{10} T_{1/2}^{\mathrm{Royer}}$ [41]	$\log_{10} T_{1/2}^{\mathrm{ELDM}}$ [71]
$^{255}104$	9.05	0.65	0.63	−0.03	0.08	0.07
$^{256}104$	8.93	0.32	0.57	0.31	0.43	0.45
$^{258}104$	9.19	−0.97	−0.23	−0.48	−0.39	−0.37
$^{259}104$	9.13	0.41	0.32	−0.33	−0.23	−0.21
$^{261}104$	8.65	0.91	1.74	1.09	1.22	1.24
$^{263}104$	8.25	3.30	3.01	2.37	2.53	2.56
$^{256}105$	9.34	0.45	0.18	−0.51	−0.41	−0.41
$^{257}105$	9.21	0.39	0.47	−0.16	−0.04	−0.04
$^{258}105$	9.50	0.75	−0.31	−0.99	−0.91	−0.90
$^{259}105$	9.62	−0.29	−0.71	−1.33	−1.26	−1.25
$^{270}105$	8.02	3.56	4.11	3.47	3.64	3.67
$^{259}106$	9.80	−0.50	−0.86	−1.45	−1.39	−1.40
$^{260}106$	9.90	−1.90	−1.54	−1.73	−1.68	−1.68
$^{261}106$	9.71	−0.73	−0.67	−1.24	−1.18	−1.19
$^{263}106$	9.40	0.03	0.15	−0.42	−0.33	−0.34
$^{267}106$	8.32	2.80	3.43	2.87	3.03	3.03
$^{269}106$	8.70	2.68	2.13	1.59	1.71	1.72
$^{271}106$	8.66	2.21	2.21	1.69	1.81	1.80
$^{260}107$	10.40	−1.46	−2.03	−2.65	−2.62	−2.62
$^{261}107$	10.50	−1.92	−2.34	−2.91	−2.89	−2.89
$^{265}107$	9.38	−0.03	0.50	−0.02	0.06	0.05
$^{266}107$	9.43	0.40	0.39	−0.18	−0.10	−0.11
$^{267}107$	8.96	1.34	1.71	1.20	1.31	1.28
$^{270}107$	9.06	1.77	1.40	0.85	0.94	0.94
$^{272}107$	9.14	0.91	1.11	0.58	0.66	0.65
$^{274}107$	8.97	1.47	1.58	1.06	1.15	1.16
$^{264}108$	10.59	−2.79	−2.71	−2.83	−2.82	−2.82

Table 1: *continued*

Parent	Q_α [MeV]	$\log_{10} T_{1/2}^{\rm Exp}$	$\log_{10} T_{1/2}^{\rm Present}$	$\log_{10} T_{1/2}^{\rm UDL}$ [70]	$\log_{10} T_{1/2}^{\rm Royer}$ [41]	$\log_{10} T_{1/2}^{\rm ELDM}$ [71]
$^{265}108$	10.47	−2.70	−2.05	−2.55	−2.54	−2.54
$^{266}108$	10.35	−2.63	−2.17	−2.27	−2.25	−2.25
$^{268}108$	9.62	0.15	−0.30	−0.38	−0.31	−0.34
$^{269}108$	9.32	1.18	0.93	0.46	0.55	0.53
$^{270}108$	9.15	0.88	1.01	0.95	1.05	1.03
$^{273}108$	9.73	−0.04	−0.32	−0.75	−0.71	−0.72
$^{275}108$	9.44	−0.53	0.45	0.03	0.09	0.08
$^{270}109$	10.18	−2.20	−1.06	−1.55	−1.52	−1.54
$^{274}109$	10.04	−0.35	−0.78	−1.24	−1.22	−1.22
$^{275}109$	10.48	−2.01	−1.97	−2.38	−2.39	−2.39
$^{276}109$	9.81	−0.14	−0.22	−0.66	−0.62	−0.64
$^{278}109$	9.59	0.55	0.35	−0.07	−0.02	−0.04
$^{267}110$	11.78	−5.00	−4.40	−4.89	−4.95	−4.76
$^{269}110$	11.51	−3.75	−3.88	−4.35	−4.39	−4.38
$^{270}110$	11.12	−3.69	−3.45	−3.49	−3.52	−3.52
$^{271}110$	10.87	−2.79	−2.51	−2.93	−2.94	−2.95
$^{273}110$	11.37	−3.77	−3.67	−4.1	−4.15	−4.13
$^{277}110$	10.83	−2.38	−2.55	−2.92	−2.95	−2.95
$^{279}110$	9.84	0.30	−0.10	−0.42	−0.39	−0.41
$^{281}110$	8.86	2.34	2.76	2.46	2.56	2.55
$^{272}111$	11.20	−2.42	−2.93	−3.38	−3.40	−3.41
$^{278}111$	10.85	−2.37	−2.26	−2.65	−2.67	−2.69
$^{279}111$	10.52	−0.76	−1.55	−1.85	−1.86	−1.88
$^{280}111$	9.89	0.54	0.12	−0.22	−0.18	−0.22
$^{281}111$	9.41	2.23	1.41	1.14	1.21	1.15
$^{282}111$	9.08	2.26	2.45	2.13	2.22	2.17
$^{277}112$	11.62	−3.16	−3.72	−4.06	−4.12	−4.12
$^{281}112$	10.46	−0.88	−1.13	−1.39	−1.38	−1.43
$^{283}112$	9.67	0.57	0.94	0.720	0.77	0.72
$^{284}112$	9.30	0.99	1.61	1.800	1.88	1.82
$^{285}112$	9.32	1.50	1.92	1.720	1.80	1.75
$^{278}113$	11.85	−3.25	−3.88	−4.26	−4.32	−4.33
$^{282}113$	10.78	−1.15	−1.58	−1.86	−1.87	−1.92
$^{283}113$	10.26	−0.99	−0.36	−0.55	−0.53	−0.60
$^{284}113$	10.11	−0.02	0.07	−0.16	−0.13	−0.20
$^{285}113$	9.84	0.50	0.73	0.570	0.61	0.55
$^{286}113$	9.79	1.30	0.91	0.700	0.74	0.68
$^{285}114$	10.54	−0.32	−0.82	−0.96	−0.96	−1.02
$^{286}114$	10.37	−0.45	−0.8	−0.54	−0.52	−0.59
$^{287}114$	10.16	−0.28	0.13	0.010	0.03	−0.03
$^{288}114$	10.07	−0.12	−0.05	0.240	0.27	0.19
$^{289}114$	9.97	0.38	0.60	0.500	0.53	0.46
$^{287}115$	10.74	−0.92	−1.06	−1.16	−1.16	−1.24
$^{288}115$	10.63	−0.72	−0.75	−0.89	−0.89	−0.97
$^{289}115$	10.49	−0.69	−0.48	−0.55	−0.54	−0.61

Table 1: *continued*

Parent	Q_α [MeV]	$\log_{10} T_{1/2}^{\mathrm{Exp}}$	$\log_{10} T_{1/2}^{\mathrm{Present}}$	$\log_{10} T_{1/2}^{\mathrm{UDL}}$ [70]	$\log_{10} T_{1/2}^{\mathrm{Royer}}$ [41]	$\log_{10} T_{1/2}^{\mathrm{ELDM}}$ [71]
$^{290}115$	10.45	0.11	−0.34	−0.46	−0.45	−0.53
$^{290}116$	10.99	−2.09	−1.84	−1.49	−1.51	−1.59
$^{291}116$	10.89	−1.55	−1.23	−1.25	−1.27	−1.35
$^{292}116$	10.77	−1.61	−1.36	−0.97	−0.98	−1.07
$^{293}116$	10.68	−1.10	−0.76	−0.75	−0.76	−0.84
$^{293}117$	11.18	−1.83	−1.68	−1.66	−1.69	−1.77
$^{294}117$	11.20	−1.29	−1.69	−1.72	−1.76	−1.84
$^{294}118$	11.81	−2.85	−3.24	−2.81	−2.88	−2.95

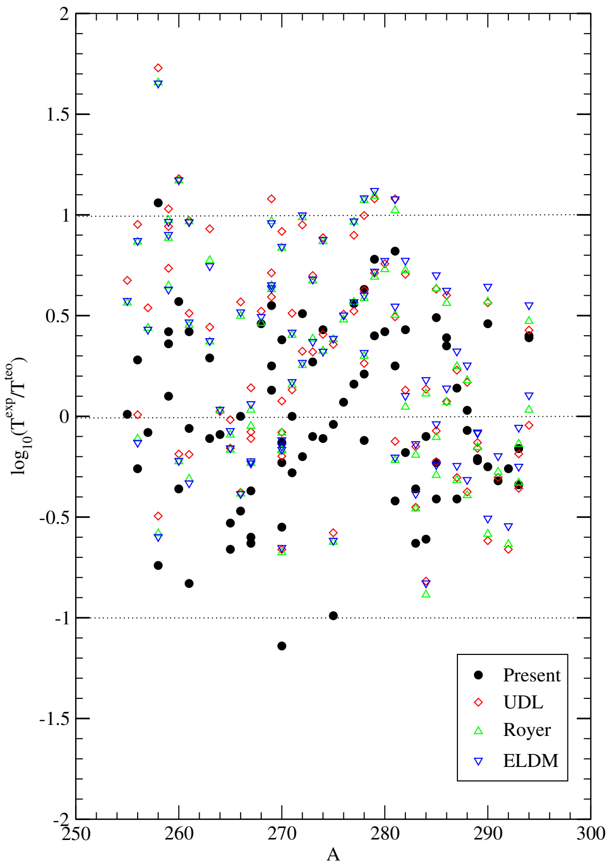

Fig. 1. The logarithmic deviation between the experimental and theoretical alpha decay half-lives of 80 superheavy nuclei with $104 \leq Z \leq 118$ *versus* the atomic mass number of the parent nucleus A for the alpha cluster (present), the UDL, Royer's formula, and ELDM models.

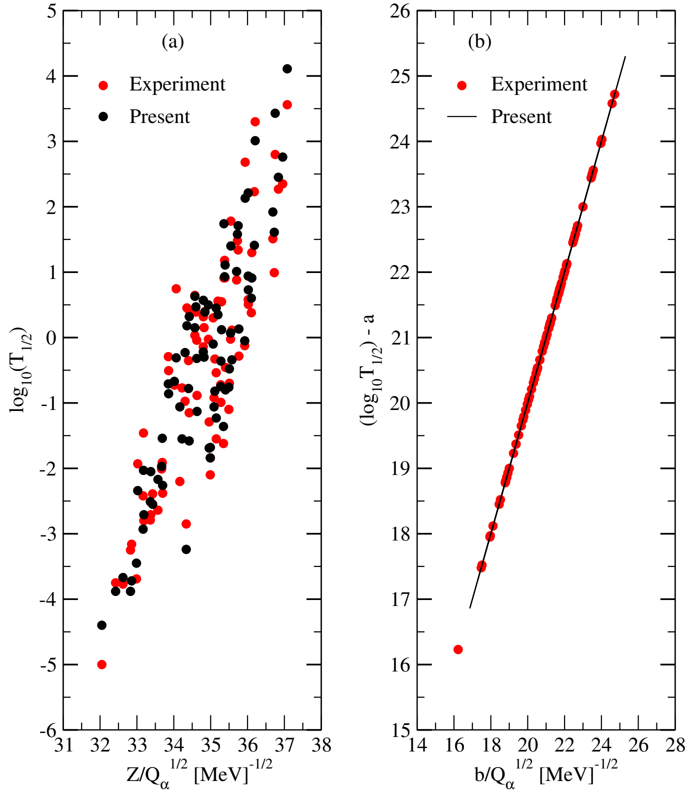

Fig. 2. (a) The logarithmic comparison between experimental and our theoretical alpha decay half-lives of 80 isotopes with $104 \leq Z \leq 118$ *versus* $\frac{Z}{\sqrt{Q_\alpha}}$. (b) Plot of the same isotopes as in (a) as $(\log_{10} T_{1/2}) - a$ *versus* $\frac{b}{\sqrt{Q_\alpha}}$. The unit of decay half-life $T_{1/2}$ is in seconds.

Relying on the success of the alpha cluster model in explaining the alpha decay half-lives of superheavy nuclei whose experimental data are known and shown in Table 1, we predict the alpha decay half-lives of 53 isotopes in the range of $104 \leq Z \leq 117$ and 48 isotopes in the range of $Z = 118$–120, whose experimental alpha decay half-lives are unknown. In Table 2, we calculate the alpha decay half-lives of superheavy nuclei with $104 \leq Z \leq 117$ and compare the UDL and Royer's formula. The theoretical alpha decay half-lives predictions of the alpha cluster, UDL and Royer's formulas are close to each other and have similar variation over the data set numbers as presented in Table 2. According to the predicted results by all three models, the second data set belonging to the $^{266}104$ nucleus has the longest alpha decay half-life, while the 29$^{\text{th}}$ data set belonging to the $^{274}110$ nucleus has the shortest decay half-life. We have also predicted the alpha decay half-lives of 48 isotopes with

$Z = 118$–120 and compared with the UDL, Royer's formula, and ELDM models in Table 3. The variation of the alpha decay half-lives as a function of the atomic mass number of the parent nuclei has the same trend for all compared theoretical models in Table 3. It is seen that the alpha decay half-lives which are obtained by Royer's formula and ELDM are very close to each other. In figure 3, we present the trend of the alpha decay half-lives *versus* neutron number of the parent nuclei in the range of $Z = 118$–120 for the alpha cluster, UDL, Royer's formula, and ELDM models. Moreover, we plot the alpha decay energies *versus* neutron number of the parent nuclei in the range of $Z = 118$–120. In figure 3, the all alpha decay models exhibit similar characteristics. While neutron numbers of the parent nuclei increase, the values of the predicted alpha decay half-lives increase and reach the maximum value at $N = 178$. Contrarily, the alpha decay energies decrease with increasing N and have a minimum value at $N = 178$. The alpha decay half-lives and alpha decay energies are approximately constant for increasing N between 178 and 184. After $N = 184$, the predicted alpha decay half-lives decrease, and alpha decay energies increase for increasing N. These trends show that the predicted alpha decay half-lives are inversely proportional to the alpha decay energies as expected in the formulas of the alpha cluster, UDL, Royer, and ELDM models. The local maximum value of alpha decay half-lives predicted by the alpha cluster, UDL, Royer, and ELDM models at $N = 178$ and $N = 184$ would be due to the shell effect.

Table 2: Comparison of the predicted alpha decay half-lives of superheavy nuclei with $104 \leq Z \leq 117$ for the alpha cluster, UDL, and Royer models. Q_α values are taken from Ref. [82]. The unit of alpha decay half-life is in seconds.

Parent	Q_α [MeV]	$\log_{10} T_{1/2}^{\text{Present}}$	$\log_{10} T_{1/2}^{\text{UDL}}$ [70]	$\log_{10} T_{1/2}^{\text{Royer}}$ [41]
$^{264}104$	8.00	3.47	3.21	3.40
$^{266}104$	7.60	4.93	4.65	4.87
$^{267}104$	7.90	4.17	3.53	3.71
$^{268}104$	8.00	3.39	3.16	3.33
$^{264}105$	8.66	2.06	1.41	1.53
$^{265}105$	8.50	2.50	1.91	2.05
$^{266}105$	8.21	3.52	2.86	3.03
$^{269}105$	8.50	2.42	1.85	1.97
$^{267}106$	8.63	2.40	1.85	1.98
$^{268}106$	8.30	3.08	2.93	3.09
$^{270}106$	9.00	0.77	0.65	0.74
$^{272}106$	8.70	1.66	1.55	1.66
$^{263}107$	10.10	−1.40	−1.94	−1.90
$^{268}107$	9.00	1.62	1.06	1.17
$^{269}107$	8.60	2.81	2.31	2.45

Table 2: *continued*

Parent	Q_α [MeV]	$\log_{10} T_{1/2}^{\text{Present}}$	$\log_{10} T_{1/2}^{\text{UDL}}$ [70]	$\log_{10} T_{1/2}^{\text{Royer}}$ [41]
$^{271}107$	9.42	0.26	−0.22	−0.16
$^{273}107$	9.10	1.15	0.68	0.76
$^{271}108$	9.51	0.34	−0.11	−0.04
$^{272}108$	9.78	−0.83	−0.87	−0.83
$^{274}108$	9.57	−0.29	−0.32	−0.27
$^{276}108$	9.28	0.49	0.48	0.55
$^{265}109$	11.10	−3.20	−3.70	−3.72
$^{267}109$	10.90	−2.79	−3.27	−3.28
$^{269}109$	10.50	−1.89	−2.34	−2.33
$^{271}109$	9.91	−0.43	−0.85	−0.81
$^{272}109$	10.40	−1.65	−2.14	−2.13
$^{273}109$	10.81	−2.71	−3.15	−3.17
$^{279}109$	9.40	0.81	0.46	0.51
$^{268}110$	11.70	−4.65	−4.74	−4.79
$^{272}110$	10.80	−2.77	−2.78	−2.79
$^{274}110$	11.70	−4.78	−4.83	−4.90
$^{275}110$	11.40	−3.77	−4.19	−4.25
$^{276}110$	11.11	−3.56	−3.56	−3.60
$^{278}110$	10.47	−2.10	−2.06	−2.07
$^{280}110$	9.81	−0.44	−0.35	−0.32
$^{273}111$	10.90	−2.32	−2.69	−2.70
$^{275}111$	11.80	−4.33	−4.74	−4.81
$^{276}111$	11.50	−3.67	−4.11	−4.16
$^{277}111$	11.20	−3.09	−3.45	−3.49
$^{283}111$	9.36	1.51	1.26	1.33
$^{276}112$	11.90	−4.27	−4.65	−4.72
$^{277}112$	11.62	−3.72	−4.06	−4.12
$^{278}112$	11.31	−3.47	−3.39	−3.43
$^{279}112$	11.04	−2.48	−2.78	−2.81
$^{280}112$	10.73	−2.17	−2.05	−2.06
$^{279}113$	11.50	−3.22	−3.51	−3.55
$^{280}113$	11.20	−2.58	−2.84	−2.87
$^{281}113$	11.00	−2.14	−2.38	−2.40
$^{287}113$	9.54	1.55	1.41	1.47
$^{291}115$	10.30	−0.03	−0.07	−0.06
$^{289}116$	11.10	−1.68	−1.74	−1.77
$^{291}117$	11.50	−2.37	−2.39	−2.43
$^{292}117$	11.40	−2.11	−2.17	−2.21

Table 3: Comparison of the predicted alpha decay half-lives of superheavy nuclei with $Z = 118$–120 for the alpha cluster, UDL, Royer, and ELDM models. Q_α values obtained with the WS4 mass model are taken from Ref. [71]. The unit of alpha decay half-life is in seconds.

Parent	Q_α [MeV]	$\log_{10} T_{1/2}^{\text{Present}}$	$\log_{10} T_{1/2}^{\text{UDL}}$ [70]	$\log_{10} T_{1/2}^{\text{Royer}}$ [41]	$\log_{10} T_{1/2}^{\text{ELDM}}$ [71]
$^{289}118$	12.59	−4.34	−4.41	−4.50	−4.56
$^{290}118$	12.60	−4.78	−4.44	−4.54	−4.59
$^{291}118$	12.42	−4.05	−4.09	−4.18	−4.24
$^{292}118$	12.24	−4.11	−3.72	−3.81	−3.87
$^{293}118$	12.24	−3.74	−3.74	−3.83	−3.89
$^{294}118$	12.17	−4.02	−3.60	−3.70	—
$^{295}118$	11.90	−3.08	−3.03	−3.10	−3.18
$^{296}118$	11.75	−3.17	−2.71	−2.78	−2.86
$^{297}118$	12.10	−3.55	−3.50	−3.59	−3.65
$^{298}118$	12.18	−4.14	−3.68	−3.78	−3.84
$^{299}118$	12.05	−3.49	−3.42	−3.51	−3.56
$^{300}118$	11.96	−3.73	−3.23	−3.33	−3.37
$^{301}118$	12.02	−3.48	−3.38	−3.48	−3.53
$^{302}118$	12.04	−3.95	−3.44	−3.54	−3.59
$^{303}118$	12.60	−4.70	−4.63	−4.77	−4.79
$^{304}118$	13.12	−6.10	−5.67	−5.84	−5.82
$^{290}119$	13.07	−4.96	−5.08	−5.19	−5.23
$^{291}119$	13.05	−5.00	−5.05	−5.17	−5.20
$^{292}119$	12.90	−4.69	−4.77	−4.88	−4.93
$^{293}119$	12.72	−4.43	−4.43	−4.53	−4.58
$^{294}119$	12.73	−4.41	−4.46	−4.57	−4.61
$^{295}119$	12.76	−4.55	−4.54	−4.65	−4.69
$^{296}119$	12.48	−3.97	−3.98	−4.08	−4.13
$^{297}119$	12.42	−3.93	−3.87	−3.97	−4.04
$^{298}119$	12.71	−4.47	−4.48	−4.60	−4.65
$^{299}119$	12.76	−4.65	−4.59	−4.72	−4.76
$^{300}119$	12.57	−4.25	−4.22	−4.34	−4.39
$^{301}119$	12.43	−4.06	−3.95	−4.06	−4.10
$^{302}119$	12.43	−4.02	−3.96	−4.08	−4.11
$^{303}119$	12.42	−4.09	−3.95	−4.07	−4.11
$^{304}119$	12.93	−5.04	−5.00	−5.16	−5.16
$^{305}119$	13.42	−6.01	−5.96	−6.14	−6.12
$^{291}120$	13.51	−5.58	−5.64	−5.76	−5.79
$^{292}120$	13.47	−5.93	−5.58	−5.71	−5.73
$^{293}120$	13.40	−5.44	−5.46	−5.59	−5.62
$^{294}120$	13.24	−5.57	−5.17	−5.29	−5.34
$^{295}120$	13.27	−5.25	−5.24	−5.37	−5.41
$^{296}120$	13.34	−5.80	−5.39	−5.53	−5.56
$^{297}120$	13.14	−5.06	−5.02	−5.15	−5.19
$^{298}120$	13.01	−5.24	−4.78	−4.91	−4.94
$^{299}120$	13.26	−5.33	−5.28	−5.42	−5.44
$^{300}120$	13.32	−5.86	−5.41	−5.56	−5.57

Table 3: *continued*

Parent	Q_α [MeV]	$\log_{10} T_{1/2}^{\mathrm{Present}}$	$\log_{10} T_{1/2}^{\mathrm{UDL}}$ [70]	$\log_{10} T_{1/2}^{\mathrm{Royer}}$ [41]	$\log_{10} T_{1/2}^{\mathrm{ELDM}}$ [71]
$^{301}120$	13.06	−5.01	−4.92	−5.06	−5.10
$^{302}120$	12.89	−5.12	−4.60	−4.73	−4.77
$^{303}120$	12.81	−4.59	−4.45	−4.58	−4.63
$^{304}120$	12.76	−4.92	−4.36	−4.50	−4.54
$^{305}120$	13.28	−5.52	−5.40	−5.57	−5.57
$^{306}120$	13.79	−6.83	−6.37	−6.56	−6.51

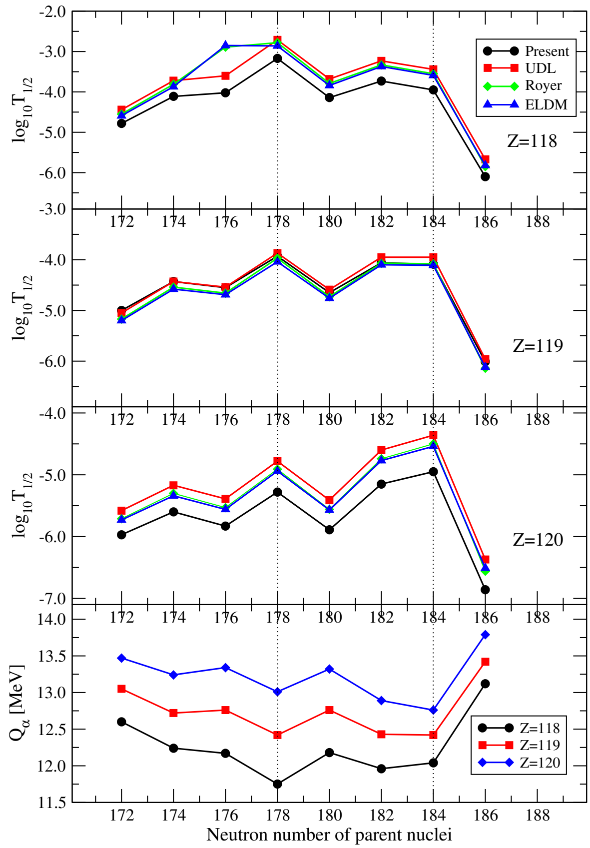

Fig. 3. Plot of the predicted alpha decay half-lives of superheavy nuclei for the alpha cluster (present), the UDL, Royer's formula, and ELDM models *versus* the neutron number of the parent nuclei with $Z = 118$–120. The bottom panel shows the variation of Q_α values *versus* neutron number of the parent nuclei. The vertical dashed lines indicate the local maximum of the alpha decay half-lives and the local minimum of the alpha decay energies at $N = 178$ and $N = 184$. The unit of decay half-life $T_{1/2}$ is in seconds.

4. Conclusion

We systematically calculate the alpha decay half-lives of 80 superheavy nuclei (SHN) whose experimental data are known for $104 \leq Z \leq 118$ employing the semi-classical WKB approximation and Bohr–Sommerfeld quantization condition which is taking into account the alpha clustering in the parent nucleus. We define the interaction potential between the alpha and daughter binary system as the modified harmonic oscillator and spherical Coulomb potentials, and obtain the analytical formula which depends on the effective potential parameters for alpha decay half-life. Using this analytical formula with only one degree of freedom, we determine the nuclear potential depth that explains the alpha decay half-lives of superheavy nuclei whose experimental data are known with $104 \leq Z \leq 118$. We calculate the r.m.s. deviation to get quantitative comparison between alpha decay half-lives of the experimental data and theoretical results for the alpha cluster, UDL and Royer models. The r.m.s. deviations of the alpha cluster, UDL, Royer, and ELDM models are $\delta = 0.44$, 0.61, 0.59, and 0.58. Thus, the alpha cluster model shows good agreement with the other three models. We also find the linear correlation between $(\log_{10} T_{1/2}) - a$ and $\frac{b}{\sqrt{Q_\alpha}}$ for the alpha decay half-life of experimental data and the alpha cluster model. We then predict the alpha decay half-lives of 53 isotopes with atomic numbers $104 \leq Z \leq 117$ and 48 isotopes with atomic numbers $Z = 118$–120 whose experimental alpha decay half-lives are unknown, using the analytical formula in Eq. (2) and optimized potential depth in Eq. (7). According to the predicted results by the alpha cluster, UDL, Royer models, the $^{266}104$ nucleus has the longest alpha decay half-life and the $^{274}110$ nucleus has the shortest decay half-live as can be seen in Table 2. The predicted alpha decay half-lives of the alpha cluster, UDL, Royer, and ELDM models have a similar trend *versus* neutron number of the parent nuclei. The fact that all models have the local maximum of the alpha decay half-lives and the local minimum of the alpha decay energies at $N = 178$ and $N = 184$ might be due to the shell closure in the parent nuclei.

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