Systematic study of α decay half-life within cluster-formation model*

Wen-Chao Dai (戴文超)[1] Jie-Dong Jiang (蒋杰栋)[1†] Yin Fan (范茵)[1] Xiao Liu (刘潇)[1] Peng-Cheng Chu (初鹏程)[2‡] Xi-Jun Wu (吴喜军)[3§] Xiao-Hua Li (李小华)[1,4,5,6,7♮]

[1]School of Nuclear Science and Technology, University of South China, Hengyang 421001, China
[2]Research Center for Theoretical Physics, Science School, Qingdao University of Technology, Qingdao 266033, China
[3]School of Math and Physics, University of South China, Hengyang 421001, China
[4]National Exemplary Base for International Sci & Tech. Collaboration of Nuclear Energy and Nuclear Safety, University of South China, Hengyang 421001, China
[5]Cooperative Innovation Center for Nuclear Fuel Cycle Technology & Equipment, University of South China, Hengyang 421001, China
[6]Key Laboratory of Low Dimensional Quantum Structures and Quantum Control, Hunan Normal University, Changsha 410081, China
[7]Key Laboratory of Advanced Nuclear Energy Design and Safety, Ministry of Education, Hengyang 421001, China

Abstract: In this study, based on the Wentzel-Kramers-Brillouin (WKB) theory, by parameterizing the assault frequency ν as a function of the α decay energy and charge radius of parent nucleus, with the α decay preformation factor P_α being calculated through the cluster-formation model (CFM), we systematically investigate the α decay half-lives of 559 nuclei from the ground state, including 177 even-even, 277 odd-A, and 105 odd-odd nuclei. The calculated results indicate that our model can effectively reproduce the experimental data, with a corresponding standard deviation of 0.408. In addition, we use this model to predict the α decay half-lives of 70 even-even, odd-A, and odd-odd nuclei with $Z = 119$ and 120. For comparison, we also use the universal decay law (UDL) proposed by Qi *et al.* [Phys. Rev. Lett 103, 072501 (2009)] and the unitary Royer formula (DZR) proposed by Deng *et al.* [Phys. Rev. C 101, 034307 (2020)]. The calculated results are in good agreement.

Keywords: α decay, half-lives, cluster-formation model (CFM)

DOI: 10.1088/1674-1137/ae042c **CSTR:** 32044.14.ChinesePhysicsC.50014103

I. INTRODUCTION

Since Becquerel first observed α decay as an unidentified radioactive phenomenon in 1896, this mode of decay has attracted widespread interest from scientists. More than a decade later, Rutherford further characterized this phenomenon as the emission of a ^{4}He particle from the parent nucleus [1]. With the advent of quantum mechanics, Gamow [2], as well as Condon and Gurney [3], attributed this process to quantum tunneling. Since then, α decay has long been perceived as one of the most powerful tools for investigating unstable, neutron-deficient, and superheavy nuclei, remaining an active area of research in nuclear physics [4−26].

With the advancement of techniques, a substantial amount of research has been conducted both experimentally [27, 28] and theoretically [29−39]. Experimentally, a series of superheavy elements have been discovered. For example, the superheavy element with atomic number $Z = 118$ has been synthesized by ^{48}Ca hot fusion reactions with an actinide Cf target in 2011 [27]. Recently, a new α-emitting isotope ^{214}U, produced by the fusion-evaporation reaction $^{182}\mathrm{W}(^{36}\mathrm{Ar}, 4n)^{214}\mathrm{U}$, was identified by employing the gas-filled recoil separator SHANS and the recoil α-correlation technique [28]. Theoretically, many famous empirical formulas have been proposed to calculate α decay half-lives. The first one was proposed by Geiger and Nuttal [40] in 1911. Their findings demonstrated that the logarithm of the half-life $\log_{10} T_{1/2}$ was linearly correlated with the inverse of the square root of α decay energy $Q_\alpha^{-1/2}$, which was known as Geiger-Nuttal law (G-N). Since then, several other noteworthy empiric-

Received 11 May 2025; Accepted 2 September 2025; Published online 3 September 2025

* Supported in part by the National Natural Science Foundation of China (12175100, 11975132), the construct program of the key discipline in hunan province, the Research Foundation of Education Bureau of Hunan Province, China (18A237, 22A0305), Hunan Provincial Department of Education Scientiffc Research Project (19A440), the Shandong Province Natural Science Foundation, China (ZR2022JQ04), the Opening Project of Cooperative Innovation Center for Nuclear Fuel Cycle Technology and Equipment, University of South China (2019KFZ10), the Innovation Group of Nuclear and Particle Physics in USC, Hunan Provincial Innovation Foundation for Postgraduate (CX20230962). Science and technology plan project of hengyang city (202150063428)

† E-mail: 1420589869@qq.com
‡ E-mail: kyois@126.com
§ E-mail: wuxijunusc@163.com
♮ E-mail: lixiaohuaphysics@126.com

al formulas have been successively proposed, including the scaling law Brown formula (SLB) [41]; universal decay law (UDL) [42, 43]; Royer formula [34] along with its improved forms such as the modified Royer formula (MR) and unitary Royer formula (DZR) [44, 45]; Viola-Seaborg formula (VS) [46] proposed in 1966 and further modified to the Viola-Seaborg-Sobiczewski formula (VSS) [47] and modified Viola-Seaborg formula (MVS) [48]; the NRDX formula and the Hatsukawa formula [49]; and more [50−55]. These formulas can effectively describe the half-life of α decay. Meanwhile, extensive theoretical frameworks, ranging from generalized liquid drop model (GLDM) [56] to microscopic approaches like the density-dependent cluster model (DDCM) [57], have been developed to describe α decay. These models emphasize the critical role of α decay preformation factors P_α in determining α decay half-lives.

Up to now, many microscopical and phenomenological models have been developed to calculate the α decay preformation factors P_α [37, 58−63]. From the microscopical perspective, the R-matrix method [37, 58−60] provides a framework to obtain P_α through the initial truncated wave functions of parent nuclei. Furthermore, the preformation factors can also be determined using the microscopical Tohsaki-Horiuchi-Schuck-Röpke wave function [61], which demonstrates particular effectiveness in addressing clustering phenomena in light nuclear systems. Using the cluster-configuration shell model, Varga *et al.* reproduced the experimental decay width of ^{212}Po and obtained its α decay preformation factor P_α = 0.23 [37, 60]. However, the calculation of purely microcosmic P_α is very difficult owing to the complexity of the nuclear many-body problem and the uncertainty of the nuclear potential. In phenomenological models, the preformation factors are typically extracted by calculating the ratio of the α decay half-lives obtained from the model and the experimental results [63–65]. In 2005, Xu and Ren [62] investigated the experimental α decay half-lives of medium-mass nuclei with $50 \leq Z \leq 82$ by employing the DDCM [57]. Their findings indicated that the α preformation factors are approximately alike for the same kinds of parent nuclei, *i.e.*, with values of 0.43 for even-even nuclei, 0.35 for odd-A nuclei, and 0.18 for odd-odd nuclei. Nevertheless, the obtained preformation factors are strongly model-dependent. Recently, Ahmed *et al.* [12, 66] proposed a new quantum-mechanical theory named cluster-formation model (CFM) to calculate the α decay preformation factors P_α of even-even nuclei, which suggests that the initial state of the parent nucleus should be a linear combination of different possible clusterization states. Subsequently, Deng *et al.* [67] and Ren *et al.* [68, 69] extended this model to calculate the preformation factors for odd-A and odd-odd nuclei.

In addition to the α decay preformation factors, recent studies have also emphasized the effect of deformation and nonlocality on the α decay half-lives. Deformation, characterized by quadrupole and hexadecapole deformation parameters, modifies the interaction potential between the emitted α particle and daughter nucleus, leading to a reduction in the α decay half-life [70]. Meanwhile, nonlocal potentials, such as the energy-dependent Perey-Buck potential and energy-independent but angular momentum-dependent Mumbai potential, lead to a reduction in α decay half-lives through nonlocal nuclear interactions. Notably, when deformation and nonlocality act together, there is no significant difference in the results for the Perey-Buck model, as the reduction induced by nonlocality in this model is already large. However, the Mumbai model shows that the reduction in α decay half-life caused by nonlocality alone is relatively small, while the introduction of deformation significantly enhances this effect [70, 71]. These findings indicate that deformation and nonlocality are important factors in calculating α decay half-life.

Assault frequency is also important in the calculation of α decay half-life. Starting from classical theory, the assault frequency can be derived as a function of the parameterized α decay energy and charge radius of the parent nucleus. Therefore, based on the above two points, we propose a model to calculate α decay half-lives, containing only four adjustable parameters, while the α decay preformation factor P_α is calculated through the CFM. The corresponding standard deviation is 0.408 for all 559 nuclei, 0.323 for even-even nuclei, 0.459 for odd-A nuclei, and 0.391 for odd-odd nuclei. In addition, we extend this model to predict the α decay half-lives of 70 even-even, odd-A, and odd-odd nuclei with Z = 119 and 120. For comparison, the formulas of UDL and DZR are also used. The prediction results of these formulas are in good agreement with each other.

The remainder of this article is organized as follows. In Sec. II, the theoretical framework for calculating α decay half-life is described briefly. In Sec. III, the calculations and discussion related to this framework are presented. Finally, a brief summary is provided in Sec. IV.

II. THEORETICAL FRAMEWORK

A. Half-lives of α decay

α decay half-life is defined as

$$T_{1/2} = \frac{\ln 2}{\lambda}, \tag{1}$$

where λ is a decay constant that can be obtained by

$$\lambda = \nu P P_\alpha. \tag{2}$$

Here, ν is the assault frequency, P denotes the penetration probability, and P_α represents the α decay preformation factors. The assault frequency ν is relevant to the α decay energy Q_α and charge radius of the parent nucleus R_p and can be parameterized as [72]

$$\log_{10}\nu = a + b\log_{10}E_\alpha^{1/2} + c\log_{10}R_p, \tag{3}$$

where E_α is the kinetic energy of the emitted α particle, which is related to the α decay energy as follows:

$$E_\alpha = \frac{A_p - 4}{A_p}Q_\alpha. \tag{4}$$

Here, A_p is the mass number of a parent nucleus. Therefore, the assault frequency ν can be expressed as

$$\log_{10}\nu = a + b\log_{10}(\frac{A_p - 4}{A_p}Q_\alpha)^{1/2} + c\log_{10}R_p, \tag{5}$$

where a, b, and c are adjustable parameters. Charge radius R_p is given by [73]

$$R_p = r_0\left(1 - r_1\frac{N_p - Z_p}{Z_p} + r_2\frac{1}{Z_p}\right)Z_p^{1/3}, \tag{6}$$

where N_p is the neutron number of a parent nucleus, and Z_p is the charge number of a parent nucleus. $r_0 = 1.5579$ fm, $r_1 = -0.0835$, and $r_2 = 1.0652$ are taken from Ref. [73].

The penetration probability P, calculated by the Wentzel-Kramers-Brillouin (WKB) approximation, is expressed as

$$P = \exp\left\{-\frac{2}{\hbar}\int_{R_0}^{R_2}\sqrt{2\mu[V(r) - Q_\alpha]}\mathrm{d}r\right\}. \tag{7}$$

Here, $V(r)$ is the total interaction potential between the emitted α particle and daughter nucleus. $\mu = m_\alpha m_d/(m_\alpha + m_d)$ is the reduced mass of the α particle and daughter nucleus in the center-of-mass coordinate, with m_d and m_α being the masses of the daughter nucleus and α particle, respectively. R_0 and R_2 are the inner and outer classical turning points of potential barrier, respectively, satisfying the conditions $V(R_0) = V(R_2) = Q_\alpha$. Here, the α decay energy Q_α can be calculated by

$$Q_\alpha = M(A,Z) - M(A-4,Z-2) - M(^4\mathrm{He}), \tag{8}$$

where $M(A,Z)$, $M(A-4,Z-2)$, and $M(^4\mathrm{He})$ are the mass excesses of the parent nucleus, daughter nucleus, and α particle.

In Eq. (7), the total interaction potential between the emitted α particle and daughter nucleus $V(r)$ contains three parts: nuclear potential $V_N(r)$, Coulomb potential $V_C(r)$, and centrifugal potential $V_l(r)$. This can be expressed as

$$V(r) = V_N(r) + V_C(r) + V_l(r). \tag{9}$$

In the case of favored α decay, a schematic diagram of α-daughter nucleus interaction potential $V(r)$ is shown in Fig. 1. R_1 is the position of the highest barrier point. From this figure, we can see that the potential $V(r)$ is divided into two parts. In the first part with $r < R_1$ ($R_1 = R_d + R_\alpha$ is the separating radius with R_d and R_α being the radii of daughter nucleus and emitted α particle, respectively), the potential $V(r)$ is expressed as $V_i(r)$, while it can be approximated by the Coulomb barrier for the second part with $r \geq R_1$.

From this perspective, the general form of Eq. (7) can be divided into two terms as

$$P = \exp\left\{-\frac{2}{\hbar}\int_{R_0}^{R_1}\sqrt{2\mu[V_i(r) - Q_\alpha]}\mathrm{d}r\right\} \times\exp\left\{-\frac{2}{\hbar}\int_{R_1}^{R_2}\sqrt{2\mu\left(\frac{2Z_d e^2}{r} - Q_\alpha\right)}\mathrm{d}r\right\}, \tag{10}$$

which are denoted as P_1 and P_2, respectively. The first term P_1 is the α decay preformation factors. Due to the complexity of the nuclear potential $V_N(r)$, P_1 cannot be integrated to obtain an analytical form. Therefore, in this work, we use the CFM to calculate it, as presented in the following. The second term P_2 can be given in analytical form as

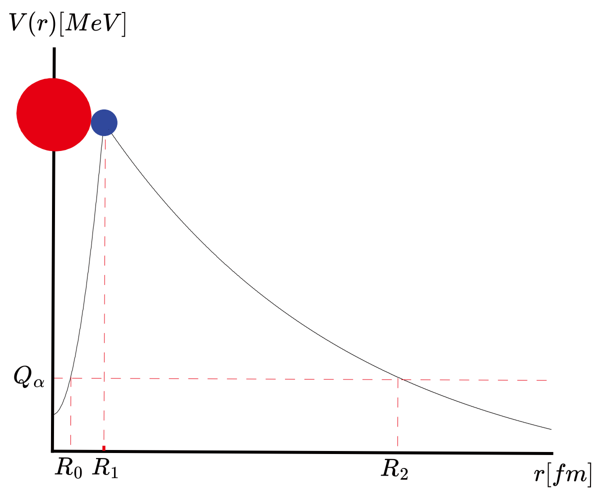

Fig. 1. (color online) Schematic diagram of α-daughter nucleus interaction potential $V(r)$.

$$P_2 = \exp\left\{-\frac{8e^2}{\hbar}\sqrt{2mZ_d}\left(\frac{A_d}{A_p Q\alpha}\right)^{1/2} \times\left[\arccos\sqrt{X}-\sqrt{X(1-X)}\right]\right\}, \tag{11}$$

where m is the mass of one atomic mass unit, Z_d is the charge number of a daughter nucleus. X is the ratio of radius R_1 to R_2, which can be expressed as

$$X = \frac{R_1}{R_2} = r\left(A_d^{1/3}+A_\alpha^{1/3}\right)\times\frac{Q_\alpha}{2Z_d e^2}. \tag{12}$$

Here, $r = 1.2249$ fm is the radius constant taken from Ref. [74], and A_d and A_α are the mass numbers of the daughter nucleus and α particle, respectively.

According to the calculation of the WKB barrier penetration probability, in the process of favored α decay, the angular momentum l carried away by the emitted α particle is equal to zero. Nevertheless, in the process of unfavored α decay, the emitted α particle takes on a non-zero angular momentum, which introduces a non-zero centrifugal potential to the total α particle-daughter nucleus interaction potential. The presence of the centrifugal potential will lead to a higher total barrier, resulting in a lower pentration probability and ultimately a longer α decay half-life. There are two methods to deal with this effect on the unfavored α decay half-lives: introducing the terms of orbital angular momentum $l(l+1)$ [42, 43, 75−78] or $\sqrt{l(l+1)}$ [75] into empirical formulas. In this work, we choose $l(l+1)$ to consider this effect and incorporate it into the original formula presented in Eq. (1). Therefore, the unified formula can be written as

$$\log_{10}T_{1/2} = \log_{10}(\ln 2)-\log_{10}\nu-\log_{10}P -\log_{10}P_\alpha+dl(l+1), \tag{13}$$

where d is an adjustable parameter.

B. Cluster-formation model

Within the CFM [12, 66−69], the total clusterization state Ψ of the parent nuclei is assumed to be a linear combination of all its n possible clusterization states Ψ_i. This can be expressed as

$$\Psi = \sum_{i=1}^{n} a_i\Psi_i, \tag{14}$$

$$a_i = \int \Psi_i^*\Psi\,\mathrm{d}\tau, \tag{15}$$

where a_i denotes the superposition coefficient of Ψ_i, on the basis of the orthogonality condition

$$\sum_{i=1}^{n}|a_i|^2 = 1. \tag{16}$$

The total wave function is an eigenfunction of the total Hamiltonian H. Similarly, H can be expressed as

$$H = \sum_{i=1}^{N} H_i, \tag{17}$$

where H_i is the Hamiltonian for the i-th clusterization state Ψ_i. Because all the clusters describe the same nucleus, they are assumed to share the same total energy E of the total wave function. Therefore, the total energy E can be expressed as

$$E = \sum_{i=1}^{n}|a_i|^2 E = \sum_{i=1}^{n} E_{fi}, \tag{18}$$

where E_{fi} denotes the formation energy of a cluster in the ith clusterization state Ψ_i. Then, the α decay preformation factors P_α can be obtained by

$$P_\alpha = \frac{E_{f\alpha}}{E}, \tag{19}$$

where $E_{f\alpha}$ is the formation energy of the α cluster. E is composed of $E_{f\alpha}$ and the interaction energy between the α cluster and daughter nuclei. In the framework of CFM [12, 67−69], the α cluster-formation energy $E_{f\alpha}$ and total energy E can be expressed as four different cases as follows:

Case I for even-even nuclei:

$$E_{f\alpha} = 3B(A,Z)+B(A-4,Z-2) -2B(A-1,Z-1)-2B(A-1,Z), \tag{20a}$$

$$E = B(A,Z)-B(A-4,Z-2); \tag{20b}$$

Case II for even Z-odd N, *i.e.*, even-odd nuclei:

$$E_{f\alpha} = 3B(A-1,Z)+B(A-5,Z-2) -2B(A-2,Z-1)-2B(A-2,Z), \tag{21a}$$

$$E = B(A,Z)-B(A-5,Z-2); \tag{21b}$$

Case III for odd Z-even N, *i.e.*, odd-even nuclei:

$$E_{f\alpha} = 3B(A-1,Z-1) + B(A-5,Z-3) - 2B(A-2,Z-2) - 2B(A-2,Z-1), \tag{22a}$$

$$E = B(A,Z) - B(A-5,Z-3); \tag{22b}$$

Case IV for doubly odd nuclei:

$$E_{f\alpha} = 3B(A-2,Z-1) + B(A-6,Z-3) - 2B(A-3,Z-2) - 2B(A-3,Z-1), \tag{23a}$$

$$E = B(A,Z) - B(A-6,Z-3); \tag{23b}$$

where $B(A,Z)$ denotes the binding energy of the nucleus with mass number A and proton number Z.

C. Semi-empirical formula

1. *Universal decay law*

In 2009, a linear expression for charged-particle emissions was proposed by Qi *et al.* [42–43] based on the α-like R-matrix theory and named as UDL. It can be expressed as

$$\log_{10}(T_{1/2}) = aZ_cZ_d\sqrt{\frac{\mathcal{A}}{Q_c}} + b\sqrt{\mathcal{A}Z_cZ_d\left(A_c^{1/3}+A_d^{1/3}\right)} + c, \tag{24}$$

where $\mathcal{A} = \dfrac{A_cA_d}{A_c+A_d}$ is the reduced mass of the emitted cluster-daughter nucleus system measured in units of the nucleon mass, and a, b, and c are adjustable parameters.

2. *Unitary Royer formula*

Based on the Royer formula [34], considering the effect of angular momentum, Deng *et al.* [45] proposed a formula to calculate α decay half-lives, which can be expressed as

$$\log_{10}T_{1/2} = a + bA^{1/6}\sqrt{Z} + c\frac{Z}{\sqrt{Q\alpha}} + dl(l+1) + h. \tag{25}$$

Here A, Z, Q_α, and l represent the mass number, proton number, α decay energy of parent nuclei, and angular momentum taken away by the emitted α particle, respectively. a, b, c, and d are adjustable parameters. The values of h for different α decay cases are expressed as

$$h = \begin{cases} 0, & \text{for even}-\text{even nuclei}, \\ 0.2812, & \text{for odd } Z-\text{even } N \text{ nuclei}, \\ 0.3625, & \text{for even } Z-\text{odd } N \text{ nuclei}, \\ 0.7486, & \text{for odd}-\text{odd nuclei}. \end{cases} \tag{26}$$

III. RESULTS AND DISCUSSION

Based on WKB theory, considering the α decay preformation factors P_α, we propose a model to calculate α decay half-lives of 559 nuclei from the ground state. Using the minimum standard deviation between experimental data and calculated data as the objective, function whose detailed information is provided later, we obtain the coefficients a, b, c, and d, as shown in the Table 1. To compare the calculated results under the same conditions, we refitted the experimental data and obtained the parameter results for the UDL and DZR, as shown in Tables 2−3. In this study, the standard deviation σ can be defined as follows:

$$\sigma = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\log_{10}T_{1/2}^{\rm exp} - \log_{10}T_{1/2}^{\rm cal}\right)^2\right]^{1/2}, \tag{27}$$

Table 1. Parameter fitting results of Eq. (13) for three different types of nuclei.

Parameters	*e-e*	*e-o*	*o-o*
a	21.1958	23.4998	26.7499
b	−1.8435	0.7241	2.25913
c	0.5001	−2.8591	−8.4193
d	0	0.2784	0.2721

Table 2. Same as Table 1 but for the UDL.

Parameters	*e-e*	*e-o*	*o-o*
a	0.4101	0.418	0.4062
b	−0.4218	−0.4024	−0.3724
c	−21.9524	−23.8632	−24.0723

Table 3. Same as Table 1 but for the DZR.

Parameters	*e−e*	*e−o*	*o−e*	*o−o*
a	−25.627	−28.22089	−27.1408	28.0910
b	−1.1559	−1.0000	−1.1410	−1.1270
c	1.5912	1.5625	1.6251	1.6408
d	0	0.0468	0.0625	0.0625

where $\log_{10} T_{1/2}^{\rm exp}$ and $\log_{10} T_{1/2}^{\rm cal}$ are the logarithmic forms of experimental α decay half-lives and the calculated ones, respectively. n is the number of nuclei involved in different decay cases. The standard deviation σ of the calculated results for the three models and/or formulas is shown in Table 4. From this table, we can clearly see that the standard deviation σ of our model only is 0.408 for all 559 nuclei, 0.323 for 177 even-even nuclei, 0.459 for 277 odd-A nuclei, and 0.391 for 105 odd-odd nuclei. These values are smaller than those of the UDL and DZR results, which proves that our model achieves satisfactory results.

To show the concrete results, we use these formulas to calculate α decay half-lives of even-even, odd-A, and odd-odd nuclei. The detailed calculated results are listed in Tables 5−7. In these tables, the first three columns represent the parent nucleus, experimentally measured α decay energy Q_α, and α decay preformation factors calculated using the CFM, respectively. The fourth to seventh columns represent the experimental half-life data for α decay, as well as those calculated using our model, UDL, and DZR in logarithmic form, denoted as $\log_{10} T_{1/2}^{\rm exp}$, $\log_{10} T_{1/2}^{\rm cal}$, $\log_{10} T_{1/2}^{\rm UDL}$, $\log_{10} T_{1/2}^{\rm DZR}$, respectively. For Tables 6−7, the eighth column represents the angular momentum l taken away by the α particle. These three tables show that our calculated results agree closely with the experimental data for most nuclei, with some exceptions such as ^{185}Pt, ^{205}Ac, ^{209}Bi, ^{210}Po, ^{227}Np, ^{230}Np, ^{245}Bk, ^{247}Cm, ^{249}Cf, ^{251}Fm, ^{255}Md, ^{257}Md, ^{258}Md, ^{268}Hs, and ^{282}Ds.

For a more intuitive comparison of the results, Figs. 2−4 plot the differences between the experimental α decay half-lives and those calculated using our model, UDL, and DZR in logarithmic form. It is evident that the differences calculated by our model are more concentrated near zero, indicating that our calculation results are closer to the experimental values. Except for a few nuclei, the differences for all 559 nuclei fall between −0.5 and 0.5. For ^{185}Pt, ^{268}Hs, and ^{282}Ds, it may be caused by deformation effects [82]. Meanwhile, for ^{209}Bi, ^{210}Po, ^{245}Bk, ^{247}Cm, ^{249}Cf, ^{251}Fm, ^{255}Md, ^{257}Md, and ^{258}Md, the larger errors are likely influenced by the shell effects at $N = 126$ and $N = 152$ [83].

Table 4. Standard deviations σ between experimental α decay half-lives and those calculated using our model, the UDL and the DZR for 177 even-even nuclei, 277 odd-A nuclei, and 105 odd-odd nuclei.

Formulas	Total	*e-e*	*e-o*	*o-o*
Our model	0.408	0.323	0.459	0.391
UDL	0.589	0.349	0.633	0.632
DZR	0.436	0.337	0.493	0.423

As is known, the half-lives of α decay show a very strong sensitivity to the α decay energy Q_α. Therefore, selecting a precise Q_α becomes one of the key problems in prediction. In 2016, Sobiczewski *et al.* systematically compared nine different mass models: Möller *et al.* (FRDM) [84], Duflo and Zuker (DZ) [85], Nayak and Satpathy (INM) [86], Wang and Liu (WS3+) [87], Wang *et al.* (WS4+) [88, 89], Muntian *et al.* (HN) [90, 91], Kuzmina *et al.* (TCSM) [92], Goriely *et al.* (HFB31) [93], and Liran *et al.* (SE) [94] and came to the conclu-

Table 5. Comparison of experimental α decay half-lives of even-even nuclei with the calculated ones using our model, UDL, and DZR in logarithmic form. The experimental α decay half-lives are taken from Ref. [79]. The α decay energy and mass excess are taken from the latest evaluated atomic mass table AME2020 [80, 81]. The α decay energy and half-lives are in units of MeV and s, respectively.

Nuclide	Q_α	P_α	$\log_{10} T_{1/2}^{\rm exp}$	$\log_{10} T_{1/2}^{\rm cal}$	$\log_{10} T_{1/2}^{\rm UDL}$	$\log_{10} T_{1/2}^{\rm DZR}$
^{146}Sm	2.5292	0.1979	15.33	15.31	15.57	15.52
^{148}Sm	1.9870	0.1954	23.30	23.10	23.54	23.43
^{148}Gd	3.2713	0.2017	9.35	9.30	9.44	9.41
^{150}Gd	2.8071	0.2021	13.75	13.67	13.87	13.84
^{152}Gd	2.2039	0.2213	21.53	21.34	21.65	21.61
^{150}Dy	4.3511	0.2360	3.11	3.05	3.10	3.07
^{152}Dy	3.7265	0.2403	6.93	7.01	7.04	7.08
^{154}Dy	2.9451	0.2379	13.98	13.68	13.77	13.83
^{152}Er	4.9341	0.2389	1.06	1.06	1.11	1.06
^{154}Er	4.2801	0.2568	4.68	4.57	4.55	4.60
^{156}Er	3.4811	0.2521	9.99	10.15	10.16	10.25
^{154}Yb	5.4741	0.2349	−0.35	−0.41	−0.33	−0.41

Continued on next page

Table 5-continued from previous page

Nuclide	Q_α	P_α	$\log_{10} T_{1/2}^{\rm exp}$	$\log_{10} T_{1/2}^{\rm cal}$	$\log_{10} T_{1/2}^{\rm UDL}$	$\log_{10} T_{1/2}^{\rm DZR}$
^{156}Yb	4.8091	0.2572	2.41	2.70	2.69	2.73
^{156}Hf	6.0251	0.2703	−1.64	−1.70	−1.66	−1.71
^{158}Hf	5.4051	0.2463	0.81	0.83	0.85	0.85
^{160}Hf	4.9021	0.2546	3.28	3.24	3.21	3.26
^{162}Hf	4.4171	0.2411	5.69	5.94	5.91	5.98
^{158}W	6.6151	0.2408	−2.84	−2.96	−2.84	−2.97
^{160}W	6.0651	0.2732	−0.99	−0.99	−0.98	−0.98
^{162}W	5.6781	0.2441	0.42	0.56	0.57	0.57
^{164}W	5.2781	0.2506	2.22	2.34	2.31	2.36
^{166}W	4.8561	0.2309	4.74	4.46	4.44	4.49
^{168}W	4.5001	0.2357	6.20	6.48	6.44	6.52
^{180}W	2.5153	0.1621	25.70	24.84	25.19	24.99
^{162}Os	6.7651	0.2373	−2.68	−2.67	−2.55	−2.66
^{164}Os	6.4851	0.2708	−1.66	−1.72	−1.70	−1.72
^{166}Os	6.1421	0.2472	−0.59	−0.46	−0.44	−0.46
^{168}Os	5.8161	0.2474	0.68	0.83	0.82	0.85
^{170}Os	5.5361	0.2373	1.89	2.04	2.02	2.05
^{172}Os	5.2241	0.2397	3.21	3.50	3.45	3.52
^{174}Os	4.8711	0.2259	5.25	5.33	5.29	5.36
^{186}Os	2.8212	0.1569	22.80	22.19	22.46	22.29
^{166}Pt	7.2951	0.2381	−3.53	−3.61	−3.47	−3.61
^{168}Pt	6.9851	0.2725	−2.69	−2.65	−2.61	−2.65
^{170}Pt	6.7081	0.2420	−1.86	−1.74	−1.68	−1.74
^{172}Pt	6.4631	0.2545	−0.99	−0.89	−0.88	−0.88
^{174}Pt	6.1833	0.2471	0.06	0.16	0.15	0.16
^{176}Pt	5.8851	0.2605	1.20	1.36	1.30	1.37
^{178}Pt	5.5731	0.2267	2.43	2.72	2.70	2.73
^{180}Pt	5.2761	0.2051	4.03	4.14	4.13	4.15
^{182}Pt	4.9511	0.1868	5.62	5.83	5.85	5.85
^{184}Pt	4.5991	0.1858	7.77	7.88	7.89	7.90
^{186}Pt	4.3201	0.1732	9.73	9.67	9.71	9.70
^{188}Pt	4.0067	0.2161	12.53	11.91	11.86	11.94
^{190}Pt	3.2686	0.2031	19.18	18.48	18.54	18.54
^{172}Hg	7.5251	0.2767	−3.64	−3.61	−3.55	−3.60
^{174}Hg	7.2331	0.2487	−2.70	−2.73	−2.66	−2.72
^{176}Hg	6.8971	0.2674	−1.65	−1.64	−1.64	−1.63
^{178}Hg	6.5773	0.2584	−0.53	−0.52	−0.54	−0.51
^{180}Hg	6.2581	0.2651	0.73	0.68	0.62	0.69
^{182}Hg	5.9951	0.2540	1.89	1.74	1.67	1.75
^{184}Hg	5.6601	0.2418	3.44	3.21	3.13	3.22
^{186}Hg	5.2041	0.2469	5.70	5.46	5.34	5.47

Continued on next page

Table 5-continued from previous page

Nuclide	Q_α	P_α	$\log_{10} T_{1/2}^{\rm exp}$	$\log_{10} T_{1/2}^{\rm cal}$	$\log_{10} T_{1/2}^{\rm UDL}$	$\log_{10} T_{1/2}^{\rm DZR}$
^{188}Hg	4.7091	0.2387	8.72	8.26	8.15	8.29
^{180}Pb	7.4191	0.2476	−2.39	−2.61	−2.55	−2.60
^{182}Pb	7.0651	0.2342	−1.26	−1.47	−1.43	−1.46
^{184}Pb	6.7741	0.2357	−0.21	−0.47	−0.46	−0.46
^{186}Pb	6.4711	0.2301	1.07	0.65	0.63	0.66
^{188}Pb	6.1091	0.2215	2.47	2.10	2.06	2.11
^{190}Pb	5.6971	0.2155	4.24	3.93	3.87	3.94
^{192}Pb	5.2211	0.2040	6.55	6.32	6.26	6.33
^{194}Pb	4.7381	0.1946	9.94	9.11	9.06	9.13
^{210}Pb	3.7927	0.1066	16.57	15.86	16.08	15.85
^{188}Po	8.0831	0.2750	−3.57	−3.97	−3.91	−3.97
^{190}Po	7.6931	0.2619	−2.61	−2.84	−2.81	−2.84
^{192}Po	7.3201	0.2571	−1.49	−1.67	−1.68	−1.67
^{194}Po	6.9871	0.2352	−0.41	−0.55	−0.56	−0.55
^{196}Po	6.6581	0.2160	0.78	0.64	0.63	0.64
^{198}Po	6.3101	0.2032	2.27	2.01	1.99	2.00
^{200}Po	5.9811	0.1837	3.79	3.41	3.41	3.41
^{202}Po	5.7001	0.1767	5.14	4.70	4.69	4.69
^{204}Po	5.4851	0.1579	6.27	5.75	5.77	5.74
^{206}Po	5.3271	0.1452	7.14	6.55	6.60	6.54
^{208}Po	5.2157	0.1350	7.96	7.13	7.20	7.11
^{210}Po	5.4075	0.1059	7.08	6.05	6.23	6.02
^{212}Po	8.9542	0.2210	−6.53	−6.76	−6.46	−6.83
^{214}Po	7.8335	0.2134	−3.79	−3.71	−3.58	−3.78
^{216}Po	6.9063	0.2046	−0.84	−0.65	−0.63	−0.72
^{218}Po	6.1148	0.1956	2.27	2.49	2.45	2.43
^{194}Rn	7.8631	0.2614	−3.11	−2.63	−2.61	−2.62
^{196}Rn	7.6161	0.2563	−2.33	−1.89	−1.89	−1.88
^{198}Rn	7.3501	0.2390	−1.16	−1.04	−1.05	−1.03
^{200}Rn	7.0441	0.2213	0.07	0.00	−0.01	0.01
^{202}Rn	6.7731	0.2094	1.09	0.99	0.97	0.99
^{204}Rn	6.5471	0.1912	2.01	1.85	1.84	1.84
^{206}Rn	6.3841	0.1803	2.74	2.49	2.49	2.48
^{208}Rn	6.2611	0.1626	3.37	2.98	3.02	2.97
^{210}Rn	6.1591	0.1515	3.95	3.39	3.45	3.38
^{212}Rn	6.3853	0.1206	3.16	2.37	2.55	2.35
^{214}Rn	9.2082	0.2291	−6.59	−6.70	−6.42	−6.75
^{216}Rn	8.1975	0.2368	−4.54	−4.04	−3.94	−4.09
^{218}Rn	7.2625	0.2342	−1.47	−1.10	−1.12	−1.15
^{220}Rn	6.4048	0.2208	1.75	2.15	2.06	2.11
^{222}Rn	5.5904	0.2218	5.52	5.92	5.75	5.87

Continued on next page

Table 5-continued from previous page

Nuclide	Q_α	P_α	$\log_{10} T_{1/2}^{\rm exp}$	$\log_{10} T_{1/2}^{\rm cal}$	$\log_{10} T_{1/2}^{\rm UDL}$	$\log_{10} T_{1/2}^{\rm DZR}$
^{202}Ra	7.8801	0.2477	−2.39	−2.03	−2.02	−2.01
^{204}Ra	7.6361	0.2309	−1.22	−1.28	−1.27	−1.26
^{206}Ra	7.4161	0.2186	−0.62	−0.57	−0.57	−0.56
^{208}Ra	7.2731	0.1954	0.10	−0.10	−0.07	−0.10
^{210}Ra	7.1511	0.1871	0.60	0.30	0.34	0.30
^{214}Ra	7.2731	0.1384	0.39	−0.21	−0.36	−0.23
^{216}Ra	9.5251	0.2390	−6.76	−6.79	−6.51	−6.82
^{218}Ra	8.5411	0.2426	−4.59	−4.28	−4.18	−4.32
^{220}Ra	7.5941	0.2393	−1.74	−1.42	−1.45	−1.46
^{222}Ra	6.6777	0.1991	1.53	1.91	1.86	1.88
^{224}Ra	5.7889	0.1840	5.50	5.88	5.79	5.85
^{226}Ra	4.8707	0.1816	10.70	11.09	10.98	11.06
^{210}Th	8.0691	0.2341	−1.80	−1.96	−1.95	−1.95
^{212}Th	7.9581	0.1957	−1.50	−1.65	−1.57	−1.64
^{214}Th	7.8271	0.1951	−1.06	−1.27	−1.20	−1.26
^{216}Th	8.0731	0.1585	−1.58	−2.09	−1.90	−2.09
^{218}Th	9.8491	0.2506	−6.91	−6.89	−6.62	−6.90
^{220}Th	8.9741	0.2432	−4.99	−4.75	−4.62	−4.77
^{222}Th	8.1321	0.2324	−2.65	−2.38	−2.35	−2.39
^{224}Th	7.2991	0.1981	0.02	0.37	0.36	0.35
^{226}Th	6.4531	0.1822	3.27	3.70	3.64	3.68
^{228}Th	5.5202	0.1831	7.78	8.24	8.12	8.22
^{230}Th	4.7700	0.1826	12.38	12.82	12.70	12.80
^{232}Th	4.0816	0.1601	17.65	18.10	18.07	18.07
^{218}U	8.7751	0.1880	−3.45	−3.42	−3.25	−3.41
^{222}U	9.4781	0.2446	−5.33	−5.36	−5.20	−5.36
^{224}U	8.6281	0.2472	−3.40	−3.11	−3.08	−3.11
^{226}U	7.7011	0.2075	−0.57	−0.24	−0.26	−0.24
^{228}U	6.7991	0.1905	2.75	3.12	3.04	3.11
^{230}U	5.9921	0.1871	6.24	6.74	6.61	6.73
^{232}U	5.4136	0.1688	9.34	9.82	9.71	9.81
^{234}U	4.8576	0.1502	12.89	13.29	13.23	13.27
^{236}U	4.5730	0.1532	14.87	15.29	15.23	15.27
^{238}U	4.2698	0.1374	17.15	17.65	17.66	17.62
^{230}Pu	7.1781	0.2015	2.02	2.45	2.36	2.46
^{232}Pu	6.7161	0.1647	4.00	4.31	4.25	4.31
^{234}Pu	6.3101	0.1517	5.72	6.10	6.05	6.10
^{236}Pu	5.8672	0.1398	7.96	8.27	8.24	8.26
^{238}Pu	5.5932	0.1450	9.44	9.73	9.67	9.72
^{240}Pu	5.2558	0.1293	11.32	11.70	11.68	11.68
^{242}Pu	4.9843	0.1326	13.07	13.42	13.39	13.39

Continued on next page

Table 5-continued from previous page

Nuclide	Q_α	P_α	$\log_{10} T_{1/2}^{\text{exp}}$	$\log_{10} T_{1/2}^{\text{cal}}$	$\log_{10} T_{1/2}^{\text{UDL}}$	$\log_{10} T_{1/2}^{\text{DZR}}$
^{244}Pu	4.6656	0.1268	15.41	15.64	15.64	15.60
^{234}Cm	7.3651	0.1943	2.28	2.53	2.43	2.54
^{236}Cm	7.0671	0.1573	3.35	3.67	3.64	3.68
^{238}Cm	6.6701	0.1366	5.31	5.32	5.32	5.32
^{240}Cm	6.3978	0.1373	6.42	6.53	6.51	6.53
^{242}Cm	6.2157	0.1222	7.15	7.38	7.39	7.37
^{244}Cm	5.9016	0.1444	8.76	8.96	8.88	8.94
^{246}Cm	5.4751	0.1421	11.17	11.33	11.25	11.31
^{248}Cm	5.1618	0.1462	13.08	13.25	13.15	13.22
^{238}Cf	8.1331	0.1854	−0.08	0.53	0.51	0.57
^{240}Cf	7.7111	0.1496	1.61	1.98	2.00	2.00
^{242}Cf	7.5171	0.1451	2.53	2.66	2.68	2.68
^{244}Cf	7.3290	0.1527	3.19	3.36	3.33	3.37
^{246}Cf	6.8616	0.1551	5.11	5.26	5.18	5.26
^{248}Cf	6.3613	0.1382	7.46	7.52	7.46	7.52
^{250}Cf	6.1285	0.1358	8.62	8.65	8.59	8.64
^{252}Cf	6.2170	0.1463	7.94	8.17	8.07	8.15
^{254}Cf	5.9261	0.1543	9.22	9.66	9.52	9.63
^{244}Fm	8.5461	0.1656	−0.51	−0.13	−0.09	−0.09
^{246}Fm	8.3791	0.1536	0.22	0.37	0.43	0.41
^{248}Fm	7.9950	0.1637	1.54	1.65	1.63	1.67
^{250}Fm	7.5569	0.1491	3.27	3.23	3.20	3.24
^{252}Fm	7.1541	0.1539	4.96	4.80	4.72	4.81
^{254}Fm	7.3073	0.1350	4.07	4.14	4.13	4.15
^{256}Fm	7.0255	0.1546	5.06	5.28	5.18	5.28
^{252}No	8.5481	0.1581	0.56	0.50	0.53	0.54
^{254}No	8.2261	0.1404	1.75	1.55	1.59	1.58
^{256}No	8.5811	0.1533	0.47	0.33	0.37	0.36
^{256}Rf	8.9261	0.1557	0.33	0.00	0.05	0.06
^{258}Rf	9.1961	0.1737	−0.59	−0.85	−0.82	−0.80
^{260}Sg	9.9001	0.1716	−1.77	−2.16	−2.06	−2.09
^{266}Hs	10.3461	0.1566	−2.41	−2.75	−2.58	−2.66
^{268}Hs	9.7651	0.1711	0.15	−1.21	−1.16	−1.14
^{270}Hs	9.0651	0.1555	0.95	0.85	0.84	0.91
^{270}Ds	11.1151	0.1793	−3.69	−4.06	−3.86	−3.95
^{282}Ds	9.1451	0.1958	2.40	1.15	1.02	1.21
^{286}Cn	9.2351	0.1836	1.48	1.55	1.42	1.62
^{286}Fl	10.3551	0.2085	−0.66	−1.04	−1.10	−0.94
^{288}Fl	10.0751	0.1976	−0.19	−0.29	−0.37	−0.20
^{290}Lv	10.9951	0.2069	−2.05	−2.12	−2.12	−1.99
^{292}Lv	10.7851	0.2016	−1.80	−1.61	−1.63	−1.49
^{294}Og	11.8353	0.2112	−3.15	−3.58	−3.49	−3.43

Table 6. Same as Table 5 but for odd-A nuclei. The column of the l term that appears for the first time is the angular momentum carried away by an α particle.

Nuclide	Q_α/MeV	P_α	$\log_{10} T_{1/2}^{\rm exp}$	$\log_{10} T_{1/2}^{\rm cal}$	$\log_{10} T_{1/2}^{\rm UDL}$	$\log_{10} T_{1/2}^{\rm DZR}$	l
^{107}Te	4.0051	0.1721	−2.34	−2.17	−2.65	−2.97	0
^{109}I	3.9171	0.2638	−0.19	−0.66	−1.60	−1.12	2
^{113}I	2.7061	0.2190	7.30	7.17	6.91	7.24	0
^{111}Xe	3.7151	0.1794	0.85	0.52	0.15	−0.19	0
^{145}Pm	2.3221	0.1659	17.30	17.68	17.51	17.77	0
^{147}Sm	2.3114	0.1588	18.53	18.69	18.52	17.77	0
^{147}Eu	2.9912	0.1723	10.96	11.48	11.41	11.53	0
^{151}Eu	1.9640	0.1789	26.16	25.81	24.97	25.67	2
^{149}Gd	3.0995	0.1581	11.27	11.18	11.10	10.52	0
^{151}Gd	2.6522	0.1611	15.63	15.86	15.78	15.09	0
^{149}Tb	4.0781	0.1835	4.95	5.00	4.29	4.64	2
^{151}Tb	3.4957	0.1799	8.82	9.06	8.38	8.79	2
^{151}Dy	4.1800	0.1796	4.28	4.26	4.24	3.83	0
^{153}Dy	3.5591	0.1864	8.39	8.49	8.53	8.02	0
^{151}Ho	4.6441	0.2212	2.20	2.12	2.18	2.11	0
^{153}Ho	4.0161	0.2207	5.37	5.77	5.89	5.87	0
^{153}Er	4.8021	0.1777	1.84	1.91	1.89	1.56	0
^{155}Er	4.1181	0.1946	6.15	5.73	5.82	5.39	0
^{153}Tm	5.2481	0.2314	0.21	0.19	0.27	0.17	0
^{155}Tm	4.5721	0.2435	3.41	3.50	3.68	3.62	0
^{157}Tm	3.8091	0.2352	7.46	8.37	8.58	8.58	0
^{155}Yb	5.3381	0.1704	0.30	0.39	0.36	0.09	0
^{155}Lu	5.8021	0.2359	−1.12	−1.20	−1.12	−1.24	0
^{157}Hf	5.8751	0.1918	−0.91	−0.96	−0.95	−1.15	0
^{159}Hf	5.2251	0.1778	1.16	1.83	1.89	1.61	0
^{161}Hf	4.6791	0.1871	3.79	4.59	4.72	4.36	0
^{157}Ta	6.2751	0.2821	−1.98	−2.16	−2.01	−2.14	0
^{159}Ta	5.6601	0.2504	0.48	0.24	0.43	0.32	0
^{159}W	6.4551	0.1658	−2.09	−2.16	−2.23	−2.37	0
^{161}W	5.9251	0.1929	−0.25	−0.29	−0.22	−0.42	0
^{163}W	5.5181	0.1747	1.27	1.43	1.51	1.26	0
^{167}W	4.7511	0.1706	4.69	5.22	5.37	5.00	0
^{163}Re	6.0121	0.2520	0.08	−0.32	−0.11	−0.25	0
^{165}Re	5.6951	0.2537	1.03	0.94	1.20	1.07	0
^{169}Re	5.0141	0.2280	5.18	5.12	4.45	5.09	3
^{163}Os	6.6651	0.1625	−2.24	−2.08	−2.12	−2.24	0
^{165}Os	6.3351	0.1892	−1.10	−1.01	−0.94	−1.10	0
^{167}Os	5.9851	0.1750	0.21	0.33	0.42	0.22	0
^{169}Os	5.7131	0.1778	1.40	1.43	1.56	1.33	0
^{171}Os	5.3711	0.1731	2.66	2.97	3.13	2.84	0

Continued on next page

Table 6-continued from previous page

Nuclide	Q_α/MeV	P_α	$\log_{10} T_{1/2}^{\text{exp}}$	$\log_{10} T_{1/2}^{\text{cal}}$	$\log_{10} T_{1/2}^{\text{UDL}}$	$\log_{10} T_{1/2}^{\text{DZR}}$	l
^{173}Os	5.0551	0.1765	3.73	4.51	4.72	4.38	0
^{167}Ir	6.5051	0.2598	−1.17	−1.36	−1.14	−1.29	0
^{169}Ir	6.1411	0.2543	−0.18	−0.02	0.24	0.09	0
^{171}Ir	5.8651	0.2397	1.31	1.09	1.37	1.22	0
^{173}Ir	5.5411	0.2365	2.41	2.50	2.81	2.67	0
^{175}Ir	5.4301	0.2195	3.02	3.69	3.30	3.54	2
^{177}Ir	5.0821	0.1885	4.69	4.80	5.06	4.92	0
^{167}Pt	7.1651	0.1611	−3.04	−2.93	−2.99	−3.05	0
^{169}Pt	6.8651	0.1883	−2.16	−2.07	−2.01	−2.11	0
^{171}Pt	6.6051	0.1694	−1.28	−1.17	−1.11	−1.24	0
^{173}Pt	6.3581	0.1808	−0.35	−0.33	−0.21	−0.37	0
^{177}Pt	5.6431	0.1888	2.24	2.54	2.78	2.52	0
^{179}Pt	5.4121	0.1658	3.94	4.34	3.86	3.84	2
^{181}Pt	5.1501	0.1521	4.85	4.98	5.18	4.84	0
^{183}Pt	4.8221	0.1405	6.61	6.80	7.00	6.60	0
^{185}Pt	4.2801	0.1414	7.93	10.24	10.48	9.97	0
^{173}Au	6.8361	0.2665	−1.53	−1.78	−1.52	−1.70	0
^{175}Au	6.5851	0.2543	−0.65	−0.91	−0.64	−0.81	0
^{177}Au	6.2971	0.2617	0.57	0.12	0.44	0.27	0
^{179}Au	5.9811	0.2240	1.51	1.43	1.73	1.56	0
^{181}Au	5.7511	0.1988	2.70	2.45	2.72	2.56	0
^{183}Au	5.4661	0.1768	3.89	3.79	4.06	3.89	0
^{185}Au	5.1800	0.1725	4.98	5.22	5.51	5.34	0
^{173}Hg	7.3751	0.1887	−3.10	−2.95	−2.90	−2.94	0
^{175}Hg	7.0751	0.1720	−2.00	−2.00	−1.94	−2.02	0
^{177}Hg	6.7351	0.1878	−0.93	−0.24	−0.77	−0.61	2
^{179}Hg	6.3511	0.1845	0.14	0.48	0.68	0.51	0
^{181}Hg	6.2841	0.1915	1.12	1.37	0.91	1.01	2
^{183}Hg	6.0381	0.1851	1.90	1.67	1.91	1.70	0
^{185}Hg	5.7721	0.1792	2.91	2.81	3.07	2.82	0
^{177}Tl	7.0671	0.2827	−1.61	−1.81	−1.50	−1.68	0
^{179}Tl	6.7051	0.2677	−0.14	−0.57	−0.23	−0.40	0
^{181}Tl	6.3221	0.2671	1.52	0.85	1.24	1.07	0
^{181}Pb	7.2451	0.1716	−1.41	−1.15	−1.73	−1.51	2
^{183}Pb	6.9281	0.1654	−0.27	−0.11	−0.66	−0.48	2
^{185}Pb	6.6951	0.1686	1.26	0.68	0.17	0.32	2
^{187}Pb	6.3931	0.1663	2.20	1.80	1.33	1.44	2
^{189}Pb	5.9151	0.1622	3.97	3.78	3.37	3.41	2
^{187}Bi	7.7791	0.2413	−1.43	−1.81	−3.14	−1.48	5
^{189}Bi	7.2681	0.2261	−0.16	−0.24	−1.51	0.15	5
^{191}Bi	6.4471	0.2144	1.39	1.17	1.52	1.32	0

Continued on next page

Table 6-continued from previous page

Nuclide	Q_α/MeV	P_α	$\log_{10} T_{1/2}^{\rm exp}$	$\log_{10} T_{1/2}^{\rm cal}$	$\log_{10} T_{1/2}^{\rm UDL}$	$\log_{10} T_{1/2}^{\rm DZR}$	l
^{193}Bi	6.0211	0.1986	3.26	2.95	3.32	3.12	0
^{195}Bi	5.5351	0.1858	5.78	5.23	5.64	5.44	0
^{209}Bi	3.1373	0.0938	26.80	25.45	24.12	25.85	5
^{211}Bi	6.7501	0.0903	2.11	1.56	−0.02	1.57	5
^{213}Bi	5.9881	0.0924	5.12	4.60	3.14	4.73	5
^{189}Po	7.6941	0.1906	−2.46	−1.95	−2.48	−2.22	2
^{191}Po	7.4931	0.1849	−1.66	−2.03	−1.86	−1.90	0
^{193}Po	7.0941	0.1840	−0.40	−0.75	−0.53	−0.61	0
^{195}Po	6.7491	0.1699	0.69	0.48	0.72	0.59	0
^{197}Po	6.4111	0.1577	1.80	1.79	2.05	1.87	0
^{199}Po	6.0741	0.1498	3.64	3.20	3.48	3.25	0
^{201}Po	5.7991	0.1368	4.92	4.46	4.74	4.46	0
^{203}Po	5.4961	0.1329	6.29	6.62	6.24	6.19	2
^{205}Po	5.3251	0.1198	7.19	6.85	7.13	6.76	0
^{207}Po	5.2151	0.1111	7.99	7.46	7.71	7.32	0
^{209}Po	4.9770	0.1037	9.59	8.84	9.08	8.65	0
^{211}Po	7.5946	0.0884	−0.29	−0.85	−2.54	−1.19	5
^{213}Po	8.5357	0.1804	−5.43	−5.35	−5.37	−5.33	0
^{215}Po	7.5263	0.1775	−2.75	−2.53	−2.39	−2.45	0
^{217}Po	6.6621	0.1726	0.20	0.42	0.69	0.53	0
^{219}Po	5.9161	0.1673	3.34	3.51	3.88	3.60	0
^{191}At	7.7141	0.1984	−2.68	−2.35	−2.15	−2.37	0
^{193}At	7.3891	0.2661	−1.54	−1.49	−1.11	−1.33	0
^{195}At	7.1021	0.2380	−0.54	−0.51	−0.14	−0.36	0
^{197}At	7.1051	0.2142	−0.39	−0.51	−0.18	−0.41	0
^{199}At	6.7781	0.1974	0.89	0.67	1.01	0.78	0
^{201}At	6.4731	0.1748	2.07	1.88	2.20	1.97	0
^{203}At	6.2101	0.1656	3.15	2.96	3.30	3.07	0
^{205}At	6.0191	0.1456	4.20	3.83	4.14	3.90	0
^{207}At	5.8731	0.1318	4.81	4.51	4.79	4.56	0
^{209}At	5.7571	0.1209	5.69	5.07	5.33	5.09	0
^{211}At	5.9825	0.0938	4.79	4.08	4.21	3.95	0
^{213}At	9.2537	0.1871	−6.90	−6.73	−6.84	−7.16	0
^{215}At	8.1771	0.1779	−4.43	−4.06	−3.99	−4.30	0
^{217}At	7.2021	0.1679	−1.49	−1.08	−0.87	−1.17	0
^{219}At	6.3421	0.1582	1.78	2.14	2.46	2.17	0
^{195}Rn	7.6941	0.1830	−2.15	−1.93	−1.73	−1.75	0
^{197}Rn	7.4101	0.1814	−1.27	−1.05	−0.81	−0.86	0
^{199}Rn	7.1321	0.1706	−0.23	−0.12	0.14	0.05	0
^{203}Rn	6.6301	0.1527	1.82	1.72	2.00	1.85	0
^{205}Rn	6.3861	0.1407	2.84	3.39	2.99	3.08	2

Continued on next page

Table 6-continued from previous page

Nuclide	Q_α/MeV	P_α	$\log_{10}T_{1/2}^{\rm exp}$	$\log_{10}T_{1/2}^{\rm cal}$	$\log_{10}T_{1/2}^{\rm UDL}$	$\log_{10}T_{1/2}^{\rm DZR}$	l
^{207}Rn	6.2511	0.1340	3.42	3.27	3.55	3.33	0
^{209}Rn	6.1551	0.1219	4.00	3.70	3.95	3.71	0
^{211}Rn	5.9661	0.1142	5.28	5.23	4.79	4.81	2
^{213}Rn	8.2451	0.0978	−1.71	−2.06	−3.75	−2.32	5
^{215}Rn	8.8386	0.1821	−5.64	−5.43	−5.44	−5.36	0
^{217}Rn	7.8881	0.1921	−3.23	−2.92	−2.73	−2.75	0
^{219}Rn	6.9462	0.1932	0.60	0.82	0.49	0.64	2
^{221}Rn	6.1631	0.1851	3.84	3.95	3.71	3.75	2
^{197}Fr	7.8841	0.2692	−2.64	−2.32	−1.95	−2.18	0
^{199}Fr	7.8161	0.2474	−2.18	−2.11	−1.77	−2.00	0
^{201}Fr	7.5191	0.2245	−1.20	−1.17	−0.82	−1.06	0
^{203}Fr	7.2741	0.2080	−0.26	−0.35	0.00	−0.24	0
^{205}Fr	7.0541	0.1858	0.60	0.44	0.78	0.53	0
^{207}Fr	6.8891	0.1724	1.19	1.04	1.37	1.12	0
^{209}Fr	6.7781	0.1527	1.75	1.48	1.77	1.52	0
^{211}Fr	6.6621	0.1400	2.33	1.93	2.21	1.95	0
^{213}Fr	6.9051	0.1096	1.54	1.07	1.21	0.94	0
^{215}Fr	9.5403	0.2012	−7.05	−6.76	−6.82	−7.13	0
^{217}Fr	8.4701	0.2040	−4.66	−4.21	−4.06	−4.37	0
^{219}Fr	7.4491	0.1976	−1.65	−1.20	−0.89	−1.19	0
^{221}Fr	6.4571	0.1823	2.46	3.16	2.90	2.99	2
^{223}Fr	5.5614	0.1799	7.34	7.88	7.17	8.14	4
^{203}Ra	7.7361	0.1746	−1.44	−1.39	−1.15	−1.16	0
^{205}Ra	7.4861	0.1646	−0.66	−0.59	−0.34	−0.38	0
^{207}Ra	7.2691	0.1574	0.21	0.81	0.40	0.61	2
^{209}Ra	7.1431	0.1418	0.67	0.59	0.83	0.74	0
^{211}Ra	7.0421	0.1372	1.10	0.93	1.17	1.07	0
^{213}Ra	6.8621	0.1263	2.27	2.29	1.84	1.99	2
^{215}Ra	8.8621	0.1092	−2.78	−3.04	−4.72	−3.22	5
^{217}Ra	9.1611	0.1850	−5.71	−5.56	−5.54	−5.43	0
^{219}Ra	8.1381	0.1911	−2.05	−2.24	−2.71	−2.41	2
^{221}Ra	6.8801	0.1899	1.40	1.90	1.64	1.78	2
^{223}Ra	5.9790	0.1608	5.99	5.77	5.55	5.55	2
^{205}Ac	7.8061	0.0991	−1.10	−0.04	−0.99	−0.48	3
^{207}Ac	7.8491	0.2218	−1.51	−1.53	−1.16	−1.41	0
^{209}Ac	7.7251	0.1938	−1.03	−1.11	−0.79	−1.04	0
^{211}Ac	7.5641	0.1820	−0.67	−0.60	−0.27	−0.53	0
^{213}Ac	7.4981	0.1637	−0.13	−0.36	−0.08	−0.34	0
^{215}Ac	7.7461	0.1301	−0.77	−1.11	−0.96	−1.24	0
^{217}Ac	9.8311	0.2172	−7.16	−6.81	−6.81	−7.12	0
^{219}Ac	8.8271	0.2166	−5.03	−4.49	−4.30	−4.60	0

Continued on next page

Table 6-continued from previous page

Nuclide	Q_α/MeV	P_α	$\log_{10}T_{1/2}^{\rm exp}$	$\log_{10}T_{1/2}^{\rm cal}$	$\log_{10}T_{1/2}^{\rm UDL}$	$\log_{10}T_{1/2}^{\rm DZR}$	l
^{221}Ac	7.7901	0.2087	−1.28	−1.56	−1.21	−1.51	0
^{223}Ac	6.7831	0.1695	2.10	2.73	2.46	2.54	2
^{225}Ac	5.9351	0.1535	5.93	6.45	6.25	6.34	2
^{227}Ac	5.0423	0.1491	10.70	10.69	11.24	10.97	0
^{211}Th	7.9451	0.1662	−1.32	−1.38	−1.12	−1.12	0
^{213}Th	7.8371	0.1401	−0.84	−1.00	−0.80	−0.81	0
^{215}Th	7.6641	0.1411	0.13	0.20	−0.25	−0.00	2
^{217}Th	9.4351	0.1215	−3.61	−3.82	−5.49	−3.93	5
^{219}Th	9.5031	0.1892	−5.99	−5.73	−5.69	−5.53	0
^{221}Th	8.6251	0.1869	−2.76	−2.88	−3.38	−3.02	2
^{223}Th	7.5661	0.1798	−0.22	0.28	−0.05	0.19	2
^{225}Th	6.9211	0.1555	2.77	2.63	2.33	2.48	2
^{227}Th	6.1467	0.1457	6.21	5.91	5.69	5.71	2
^{229}Th	5.1676	0.1488	11.40	11.10	10.99	10.82	2
^{211}Pa	8.4751	0.2424	−2.22	−2.73	−2.36	−2.62	0
^{213}Pa	8.3851	0.1981	−2.13	−2.42	−2.13	−2.39	0
^{215}Pa	8.2351	0.1934	−1.85	−2.01	−1.70	−1.97	0
^{217}Pa	8.4891	0.1545	−2.42	−2.68	−2.51	−2.78	0
^{219}Pa	10.1241	0.2367	−7.25	−6.86	−6.81	−7.10	0
^{221}Pa	9.2431	0.2245	−5.23	−4.88	−4.68	−4.98	0
^{223}Pa	8.3451	0.2099	−2.28	−2.50	−2.17	−2.47	0
^{225}Pa	7.4051	0.1739	0.23	1.22	0.94	1.02	2
^{227}Pa	6.5801	0.1561	3.43	3.73	4.20	3.91	0
^{229}Pa	5.8351	0.1548	7.43	7.57	7.73	7.57	1
^{231}Pa	5.1499	0.1520	12.01	11.03	11.63	11.35	0
^{219}U	9.9501	0.1401	−4.22	−4.42	−6.04	−4.43	5
^{221}U	9.8891	0.1800	−6.18	−5.95	−5.93	−5.73	0
^{223}U	9.1651	0.1833	−4.19	−3.60	−4.13	−3.71	2
^{225}U	8.0071	0.1862	−1.21	−0.40	−0.72	−0.43	2
^{227}U	7.2351	0.1586	1.82	2.26	1.99	2.18	2
^{229}U	6.4761	0.1485	4.24	4.63	5.11	4.90	0
^{231}U	5.5763	0.1481	9.95	9.73	9.63	9.54	2
^{233}U	4.9087	0.1348	12.70	13.16	13.76	13.23	0
^{223}Np	9.6551	0.2334	−5.60	−5.23	−5.03	−5.32	0
^{225}Np	8.8251	0.2306	−2.22	−3.18	−2.83	−3.12	0
^{227}Np	7.8151	0.1888	−0.29	0.85	0.32	0.78	3
^{229}Np	7.0151	0.1691	2.55	3.17	3.28	3.11	1
^{231}Np	6.3651	0.1631	5.14	5.90	6.08	5.92	1
^{233}Np	5.6281	0.1439	8.49	9.25	9.85	9.55	0
^{235}Np	5.1938	0.1265	12.12	12.23	12.42	12.25	1
^{237}Np	4.9573	0.1272	13.83	13.74	13.95	13.77	1

Continued on next page

Table 6-continued from previous page

Nuclide	Q_α/MeV	P_α	$\log_{10}T_{1/2}^{\rm exp}$	$\log_{10}T_{1/2}^{\rm cal}$	$\log_{10}T_{1/2}^{\rm UDL}$	$\log_{10}T_{1/2}^{\rm DZR}$	l
^{229}Pu	7.5931	0.1707	2.26	1.73	1.51	1.74	2
^{231}Pu	6.8391	0.1530	3.58	3.93	4.44	4.29	0
^{233}Pu	6.4141	0.1271	6.00	6.50	6.31	6.37	2
^{235}Pu	5.9511	0.1182	7.72	8.07	8.58	8.26	0
^{239}Pu	5.2444	0.1161	11.88	12.03	12.60	12.13	0
^{241}Pu	5.1401	0.1053	13.26	13.38	13.24	13.02	2
^{229}Am	8.1351	0.2148	0.26	0.23	0.05	0.14	2
^{233}Am	7.0651	0.1485	3.62	3.82	3.93	3.76	1
^{235}Am	6.5751	0.1334	5.18	5.89	6.02	5.85	1
^{237}Am	6.1951	0.1204	7.24	7.68	7.81	7.63	1
^{239}Am	5.9225	0.1230	8.63	9.01	9.18	9.00	1
^{241}Am	5.6378	0.1082	10.14	10.59	10.73	10.54	1
^{243}Am	5.4391	0.1098	11.37	11.71	11.88	11.68	1
^{233}Cm	7.4751	0.1544	2.11	2.27	2.76	2.70	0
^{235}Cm	7.2761	0.1467	3.99	3.68	3.50	3.69	2
^{241}Cm	6.1852	0.1074	8.45	8.75	8.30	8.58	3
^{243}Cm	6.1688	0.0972	8.96	8.56	8.35	8.34	2
^{245}Cm	5.6245	0.1158	11.42	11.37	11.28	11.16	2
^{247}Cm	5.3535	0.1159	14.69	12.67	12.90	12.52	1
^{245}Bk	6.4546	0.1228	8.55	7.52	7.40	7.45	2
^{247}Bk	5.8901	0.1190	10.64	10.34	10.27	10.32	2
^{249}Bk	5.5210	0.1209	12.29	12.40	12.38	12.42	2
^{239}Cf	7.7651	0.1369	1.63	1.99	2.46	2.43	0
^{241}Cf	7.4551	0.1128	2.97	3.17	3.60	3.53	0
^{243}Cf	7.4151	0.1106	3.66	4.26	3.73	4.21	3
^{245}Cf	7.2585	0.1180	3.88	3.84	4.32	4.21	0
^{247}Cf	6.5022	0.1209	7.50	7.73	7.63	7.68	2
^{249}Cf	6.2933	0.1102	10.04	8.45	8.63	8.44	1
^{251}Cf	6.1771	0.1104	10.45	10.13	9.19	10.29	5
^{253}Cf	6.0776	0.1201	8.69	9.05	9.68	9.36	0
^{241}Es	8.2551	0.1402	0.71	0.69	1.12	0.82	0
^{243}Es	8.0751	0.1327	1.55	1.27	1.71	1.40	0
^{245}Es	7.8651	0.1367	2.13	1.94	2.43	2.11	0
^{247}Es	7.4431	0.1371	3.59	3.45	4.00	3.68	0
^{249}Es	6.9413	0.1199	6.03	6.47	6.06	6.48	3
^{251}Es	6.5971	0.1153	7.36	7.02	7.60	7.27	0
^{253}Es	6.7393	0.1224	6.25	6.31	6.91	6.56	0
^{255}Es	6.4001	0.1282	7.63	7.84	8.50	8.15	0
^{243}Fm	8.6951	0.1398	−0.60	0.05	0.06	0.24	1
^{245}Fm	8.4351	0.1230	0.62	1.45	0.87	1.49	3
^{247}Fm	8.2551	0.1154	1.69	2.30	1.44	2.41	4

Continued on next page

Table 6-continued from previous page

Nuclide	Q_α/MeV	P_α	$\log_{10}T_{1/2}^{\rm exp}$	$\log_{10}T_{1/2}^{\rm cal}$	$\log_{10}T_{1/2}^{\rm UDL}$	$\log_{10}T_{1/2}^{\rm DZR}$	l
^{251}Fm	7.4251	0.1148	6.03	4.34	4.45	4.46	1
^{253}Fm	7.0529	0.1219	6.33	6.92	5.98	7.23	5
^{257}Fm	6.8631	0.1253	6.94	6.81	6.75	6.85	2
^{245}Md	9.0151	0.1583	−0.42	−0.32	−0.57	−0.50	2
^{247}Md	8.7651	0.1426	0.08	0.14	0.17	−0.02	1
^{249}Md	8.4351	0.1490	1.53	1.39	1.21	1.27	2
^{251}Md	7.9641	0.1337	3.40	2.70	2.83	2.63	1
^{253}Md	7.5651	0.1351	5.01	4.12	4.31	4.10	1
^{255}Md	7.9051	0.1164	4.36	3.19	2.98	3.02	2
^{257}Md	7.5571	0.1313	5.11	4.09	4.28	4.06	1
^{251}No	8.7551	0.1163	−0.02	0.16	0.54	0.64	0
^{253}No	8.4151	0.1186	2.23	1.58	1.63	1.78	1
^{255}No	8.2281	0.1081	2.84	2.50	2.24	2.55	2
^{257}No	8.4766	0.1192	1.46	1.61	1.36	1.70	2
^{259}No	7.8541	0.1224	3.66	3.68	3.54	3.79	2
^{253}Lr	8.9151	0.1460	−0.15	−0.08	0.40	0.08	0
^{255}Lr	8.5021	0.1273	1.49	1.23	1.71	1.39	0
^{257}Lr	9.0151	0.1364	0.78	0.83	0.02	0.94	4
^{259}Lr	8.5751	0.1360	0.90	0.90	1.40	1.07	0
^{255}Rf	9.0551	0.1210	0.49	0.31	0.32	0.56	1
^{257}Rf	8.9141	0.1170	0.75	1.00	0.74	1.14	2
^{259}Rf	9.1331	0.1319	0.49	0.27	0.02	0.45	2
^{261}Rf	8.6481	0.1252	1.06	1.05	1.54	1.62	0
^{257}Db	9.2051	0.1455	0.39	0.12	0.22	0.03	1
^{259}Db	9.5671	0.1599	−0.29	−0.97	−0.89	−1.08	1
^{263}Db	8.8351	0.1390	1.89	2.28	1.29	2.83	5
^{261}Sg	9.7141	0.1262	−0.73	−0.66	−0.96	−0.46	2
^{263}Sg	9.4051	0.1275	0.03	−0.53	−0.09	0.09	0
^{265}Sg	9.0451	0.1244	1.26	2.02	0.99	2.52	5
^{261}Bh	10.5051	0.1648	−1.89	−2.16	−2.73	−2.30	3
^{265}Hs	10.4701	0.1278	−2.71	−2.67	−2.35	−2.04	0
^{269}Hs	9.2751	0.1264	1.18	0.85	0.98	1.24	1

Table 7. Same as Table 6 but for odd-odd nuclei.

Nuclide	Q_α/MeV	P_α	$\log_{10}T_{1/2}^{\rm exp}$	$\log_{10}T_{1/2}^{\rm cal}$	$\log_{10}T_{1/2}^{\rm UDL}$	$\log_{10}T_{1/2}^{\rm DZR}$	l
^{148}Eu	4.5071	0.1400	14.70	15.30	14.33	15.11	0
^{152}Ho	4.0421	0.1682	3.12	3.20	3.03	3.11	0
^{154}Ho	5.0941	0.1714	6.56	6.05	5.77	6.00	0
^{154}Tm	4.3461	0.1709	1.17	1.23	1.20	1.17	0
^{156}Tm	5.5951	0.1835	5.12	5.20	5.06	5.22	0
^{156}Lu	4.7901	0.1678	−0.31	−0.09	−0.03	−0.15	0

Continued on next page

Table 7-continued from previous page

Nuclide	Q_α/MeV	P_α	$\log_{10}T_{1/2}^{\text{exp}}$	$\log_{10}T_{1/2}^{\text{cal}}$	$\log_{10}T_{1/2}^{\text{UDL}}$	$\log_{10}T_{1/2}^{\text{DZR}}$	l
^{158}Lu	6.1251	0.1842	3.07	3.76	3.73	3.81	0
^{158}Ta	5.0071	0.1946	−1.31	−1.38	−1.17	−1.35	0
^{162}Ta	6.6951	0.1828	3.68	4.27	3.65	4.06	2
^{160}Re	6.2451	0.1727	−2.26	−1.85	−2.28	−2.17	2
^{162}Re	5.0681	0.1977	−0.95	−0.99	−0.72	−0.91	0
^{168}Re	6.7151	0.1655	4.94	5.52	4.35	5.64	4
^{166}Ir	6.3751	0.1965	−1.95	−1.87	−1.54	−1.79	0
^{168}Ir	5.9551	0.1781	−0.64	−0.62	−0.35	−0.55	0
^{170}Ir	5.9851	0.1792	1.24	1.03	1.27	1.13	0
^{172}Ir	5.6931	0.1711	2.34	1.83	1.11	1.71	3
^{174}Ir	7.1851	0.1730	3.17	2.83	2.36	2.63	2
^{170}Au	6.9251	0.1977	−2.58	−2.67	−2.27	−2.58	0
^{172}Au	6.6951	0.1743	−1.55	−1.79	−1.45	−1.72	0
^{174}Au	6.4351	0.1843	−0.81	−1.03	−0.68	−0.93	0
^{176}Au	6.0581	0.1781	0.14	−0.08	0.24	0.02	0
^{178}Au	5.8311	0.1875	1.32	1.40	1.71	1.56	0
^{180}Au	5.5251	0.1625	3.13	3.11	2.66	2.92	2
^{182}Au	5.2341	0.1464	4.06	4.53	4.00	4.31	2
^{184}Au	4.9121	0.1327	5.19	5.41	5.45	5.45	0
^{186}Au	7.0251	0.1316	7.89	7.56	7.16	7.35	1
^{178}Tl	7.7571	0.1934	−0.39	−0.75	−0.99	−0.90	2
^{186}Bi	7.2631	0.1751	−1.83	−2.66	−2.59	−2.86	1
^{188}Bi	6.8621	0.1691	−1.22	−1.08	−1.04	−1.25	1
^{190}Bi	6.3811	0.1620	0.91	0.31	0.31	0.16	1
^{192}Bi	5.9181	0.1567	2.44	2.17	2.12	2.04	1
^{194}Bi	5.2611	0.1475	4.31	4.17	4.05	4.05	1
^{196}Bi	6.2073	0.1401	7.43	7.14	7.28	7.29	0
^{212}Bi	5.6211	0.0786	4.00	3.98	2.51	4.11	5
^{214}Bi	7.6961	0.0815	6.75	6.68	5.15	6.87	5
^{192}At	7.3341	0.1895	−1.94	−2.19	−1.66	−2.04	0
^{194}At	7.1951	0.1860	−0.54	−1.01	−0.50	−0.83	0
^{196}At	6.8891	0.1695	−0.41	−0.55	−0.09	−0.41	0
^{198}At	6.5961	0.1545	0.66	0.58	0.99	0.71	0
^{200}At	6.3541	0.1447	1.92	1.70	2.06	1.82	0
^{202}At	6.0711	0.1309	3.16	2.75	3.04	2.84	0
^{204}At	5.8871	0.1252	4.16	3.97	4.22	4.06	0
^{206}At	5.7511	0.1116	5.31	5.50	5.01	5.25	2
^{208}At	5.6311	0.1022	6.02	5.53	5.65	5.53	0
^{210}At	7.8172	0.0946	7.22	6.81	6.21	6.48	2
^{212}At	8.9880	0.0784	−0.50	−0.99	−2.35	−0.96	5
^{214}At	7.9500	0.1542	−6.25	−5.99	−5.60	−6.24	0

Continued on next page

Table 7-continued from previous page

Nuclide	Q_α/MeV	P_α	$\log_{10} T_{1/2}^{\rm exp}$	$\log_{10} T_{1/2}^{\rm cal}$	$\log_{10} T_{1/2}^{\rm UDL}$	$\log_{10} T_{1/2}^{\rm DZR}$	l
^{216}At	6.8761	0.1501	−3.52	−3.21	−2.81	−3.33	0
^{218}At	6.0531	0.1438	0.11	1.02	0.71	0.71	2
^{220}At	7.8711	0.1376	3.43	3.78	4.07	3.83	0
^{198}Fr	7.6151	0.1864	−1.82	−1.07	−1.45	−1.08	3
^{200}Fr	7.3861	0.1729	−1.32	−1.22	−0.69	−1.05	0
^{202}Fr	7.1701	0.1594	−0.43	−0.44	0.05	−0.29	0
^{204}Fr	6.9231	0.1502	0.26	0.33	0.78	0.46	0
^{206}Fr	6.7851	0.1368	1.26	1.27	1.66	1.38	0
^{208}Fr	6.6701	0.1283	1.82	1.77	2.13	1.85	0
^{210}Fr	6.5291	0.1152	2.43	2.26	2.57	2.30	0
^{212}Fr	8.5891	0.1068	3.44	3.51	3.10	3.23	2
^{214}Fr	9.1742	0.0893	−2.26	−2.53	−3.79	−2.47	5
^{216}Fr	8.0131	0.1610	−6.15	−5.78	−5.32	−5.95	0
^{218}Fr	6.8001	0.1661	−2.85	−2.69	−2.19	−2.69	0
^{220}Fr	7.9531	0.1635	1.44	1.83	1.90	1.70	1
^{206}Ac	7.7281	0.1668	−1.60	−1.56	−0.99	−1.39	0
^{208}Ac	7.5401	0.0903	−1.01	−0.61	−0.32	−0.70	0
^{212}Ac	7.3521	0.1334	−0.05	−0.21	0.25	−0.12	0
^{214}Ac	9.2411	0.1212	0.94	1.13	0.87	0.90	2
^{216}Ac	9.3831	0.1027	−3.36	−3.58	−4.74	−3.47	5
^{218}Ac	8.3481	0.1688	−6.00	−5.65	−5.12	−5.74	0
^{220}Ac	7.1381	0.1710	−1.58	−2.31	−2.41	−2.55	2
^{222}Ac	6.3271	0.1667	0.70	0.97	1.50	1.15	0
^{224}Ac	5.5061	0.1386	5.02	4.72	4.73	4.62	1
^{226}Ac	8.4151	0.1279	9.23	9.12	8.70	9.00	2
^{212}Pa	8.2751	0.1688	−2.24	−2.31	−1.68	−2.14	0
^{214}Pa	8.0991	0.1404	−1.77	−1.84	−1.30	−1.75	0
^{216}Pa	9.7031	0.1392	−0.98	−0.65	−0.78	−0.84	2
^{220}Pa	7.6931	0.1785	−6.07	−5.78	−5.18	−5.82	0
^{224}Pa	6.9871	0.1623	−0.07	0.49	0.42	0.38	2
^{226}Pa	6.2651	0.1372	2.16	2.43	2.91	2.60	0
^{228}Pa	5.4401	0.1264	6.63	6.47	5.91	6.47	3
^{230}Pa	9.3291	0.1274	10.67	10.50	10.09	10.44	2
^{224}Np	8.3351	0.1742	−4.32	−3.59	−3.59	−3.79	2
^{226}Np	7.5431	0.1739	−1.46	−1.54	−0.86	−1.33	0
^{228}Np	6.7811	0.1451	2.17	1.54	1.74	1.49	1
^{230}Np	5.0081	0.1328	3.96	5.06	4.62	5.11	3
^{236}Np	6.7951	0.1049	15.47	14.83	13.72	15.07	4
^{234}Am	6.2551	0.1153	5.55	6.42	5.41	7.04	5
^{236}Am	5.4691	0.1054	6.73	7.43	7.81	7.65	0
^{240}Am	8.1051	0.1006	10.98	11.70	11.93	11.92	0

Continued on next page

Table 7-continued from previous page

Nuclide	Q_α/MeV	P_α	$\log_{10}T_{1/2}^{\rm exp}$	$\log_{10}T_{1/2}^{\rm cal}$	$\log_{10}T_{1/2}^{\rm UDL}$	$\log_{10}T_{1/2}^{\rm DZR}$	l
^{234}Bk	8.2651	0.1480	1.40	1.36	1.40	1.37	2
^{240}Es	8.1551	0.1308	0.93	1.29	1.61	1.32	1
^{242}Es	7.9451	0.1057	1.49	1.72	1.94	1.66	1
^{244}Es	7.4951	0.1022	2.84	2.43	2.63	2.36	1
^{246}Es	7.6451	0.1068	3.66	3.66	4.24	3.90	0
^{246}Es	7.1611	0.1068	3.66	3.47	3.68	3.44	1
^{248}Es	6.7351	0.1087	5.76	5.65	5.55	5.63	2
^{252}Es	8.9451	0.0958	7.72	7.48	7.28	7.42	2
^{244}Md	8.8951	0.1347	−0.44	−0.16	0.22	−0.14	1
^{246}Md	8.1551	0.1170	−0.04	0.03	0.34	−0.02	1
^{250}Md	7.7451	0.1139	2.88	2.64	2.66	2.62	2
^{256}Md	7.2709	0.0951	4.70	4.38	4.03	4.40	3
^{258}Md	9.1651	0.1081	6.65	5.63	5.86	5.67	1
^{252}Lr	8.8251	0.1096	−0.42	−0.49	0.23	−0.28	0
^{254}Lr	8.8551	0.1102	1.22	1.44	1.23	1.50	3
^{256}Lr	9.3351	0.0992	1.52	0.81	1.10	0.74	1
^{256}Db	9.3351	0.1152	0.38	0.32	0.44	0.31	2

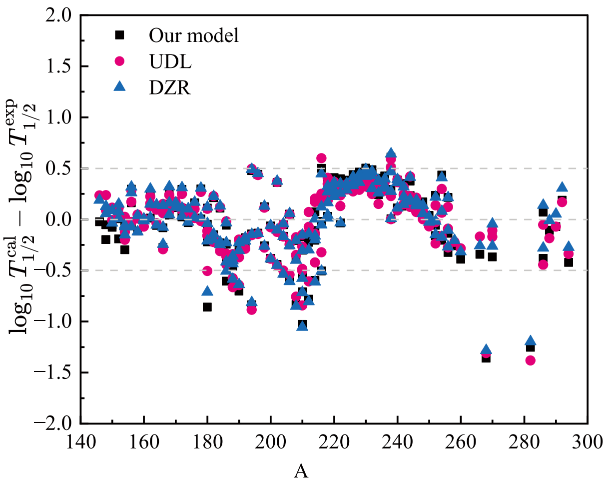

Fig. 2. (color online) Deviations between the experimental α decay half-lives and the calculated ones obtained using our model, UDL, and DZR in logarithmic form.

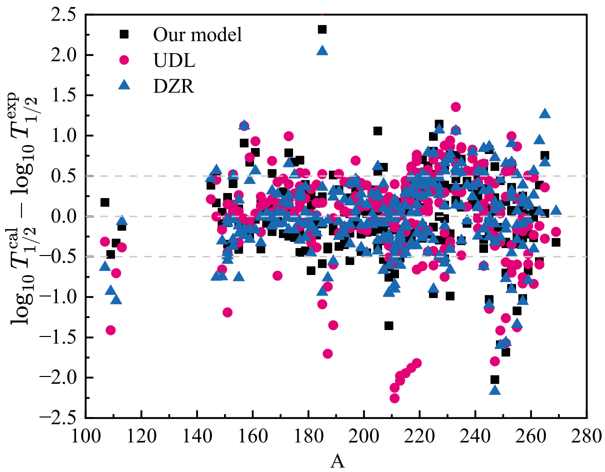

Fig. 3. (color online) Same as Fig. 2 but for odd-A nuclei.

sion that the WS3+ model is the most accurate in reproducing the experimental Q_α of superheavy nuclei. In this work, we use our model to predict the α decay half-lives of 70 even-even, odd-A, and odd-odd nuclei with $Z = 119$ and 120. The predicted results are listed in Table 8. In this table, the first to fourth columns represent the parent nucleus, α decay energy Q_α calculated using WS3+, angular momentum l carried away by the α particle, and α preformation factors calculated by the CFM, respectively. The last three, $\log_{10}T_{1/2}^{\rm cal}$, $\log_{10}T_{1/2}^{\rm UDL}$, $\log_{10}T_{1/2}^{\rm DZR}$, represent the predicted α decay half-lives in logarithmic form calculated by our model, UDL, and DZR, respectively. From this table, we can clearly see that the three predictions are quite close to each other. To visually illustrate their relationship, the logarithmic form of α decay half-lives and the Q_α values calculated by the WS3+ mass model with $Z = 119$ and 120 versus the neutron numbers of the daughter nucleus N_d, as well as the curve of the relationship between the α decay preformation factors and neutron number of the parent nucleus N, are plotted in Figs. 5−7, respectively. From Fig 5, it can be seen that the trends of the α decay half-lives for the isotopic chains with proton

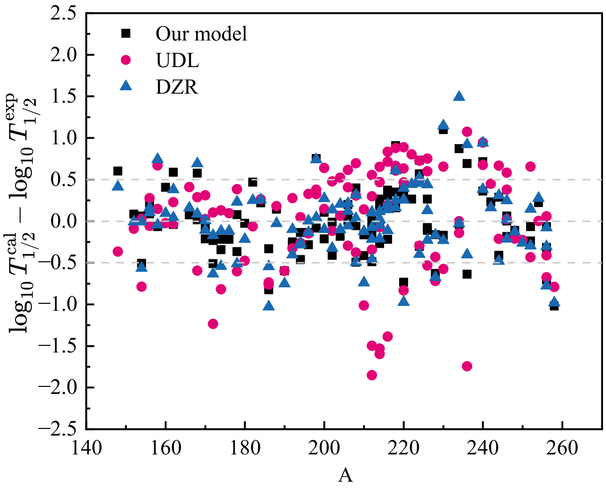

Fig. 4. (color online) Same as Fig. 2 but for odd-odd nuclei.

numbers Z = 119 and 120 predicted by our model, UDL, and DZR are consistent, and our predicted results are close to those of UDL. Furthermore, as shown in Fig. 5, for the isotope chains with Z = 119 and 120, when the neutron number of the daughter nucleus N_d is less than 176, the half-lives of α decay exhibit a slow upward trend, followed by a gradual decrease to a minimum value at N_d = 178. From N_d = 178 to N_d = 182, it keeps a steady change. Then, it suddenly drops to the lowest point at N_d = 184, after which an upward trend appears again. A similar phenomenon can also be observed on Q_α in Fig. 6. In addition, Fig. 7 clearly shows that the α decay preformation factors of even-even nuclei with Z = 120, odd-A nuclei with Z = 119, and odd-odd nuclei with Z = 119 show a trend of first decreasing and then increasing near the neutron number N = 184 of the parent nuclei.

Table 8. Predicted results of the α decay half-lives in logarithmic form for 70 even-even, odd-even, and odd-odd nuclei with Z = 119 and 120 using our model, UDL, and DZR. The α decay energy and half-lives are in units of MeV and s, respectively. The mass excesses are taken from the WS3+ mass model [87]. The spin and parity values of these nuclei are taken from Ref. [98].

Nuclide	Q_α	l	P_α	$\log_{10}T_{1/2}^{\rm cal}$	$\log_{10}T_{1/2}^{\rm UDL}$	$\log_{10}T_{1/2}^{\rm DZR}$
			Nuclei with Z=119			
^{284}119	13.7747	4	0.2181	−5.44	−6.38	−5.41
^{285}119	13.6461	2	0.2940	−5.93	−6.15	−5.65
^{286}119	13.4606	2	0.1831	−5.38	−5.80	−5.72
^{287}119	13.2830	2	0.2852	−5.31	−5.47	−4.97
^{288}119	13.1697	2	0.1838	−4.87	−5.25	−5.18
^{289}119	13.0764	2	0.2539	−4.91	−5.08	−4.58
^{290}119	12.9211	2	0.1679	−4.38	−4.77	−4.71
^{291}119	12.8677	2	0.2525	−4.54	−4.68	−4.18
^{292}119	12.7053	2	0.1706	−3.99	−4.35	−4.29
^{293}119	12.5103	2	0.2395	−3.85	−3.94	−3.45
^{294}119	12.5217	2	0.1672	−3.64	−3.98	−3.93
^{295}119	12.5701	2	0.2196	−3.96	−4.10	−3.61
^{296}119	12.3096	2	0.1553	−3.19	−3.54	−3.50
^{297}119	12.3025	2	0.1922	−3.39	−3.54	−3.05
^{298}119	12.5862	2	0.1416	−3.75	−4.18	−4.14
^{299}119	12.7275	2	0.2167	−4.33	−4.50	−4.03
^{300}119	12.5259	2	0.1596	−3.70	−4.08	−4.05
^{301}119	12.3748	0	0.2040	−4.31	−3.76	−3.66
^{302}119	12.3960	0	0.1540	−4.11	−3.83	−4.17
^{303}119	12.3691	2	0.2036	−3.64	−3.78	−3.31
^{304}119	12.8958	1	0.1608	−4.78	−4.94	−5.16
^{305}119	13.4495	2	0.2078	−5.73	−6.08	−5.62
^{306}119	13.2476	0	0.1632	−5.86	−5.69	−6.04
^{307}119	12.8167	0	0.2162	−5.30	−4.82	−4.73

Continued on next page

Table 8-continued from previous page

Nuclide	Q_α	l	P_α	$\log_{10} T_{1/2}^{\rm cal}$	$\log_{10} T_{1/2}^{\rm UDL}$	$\log_{10} T_{1/2}^{\rm DZR}$
^{308}119	12.0652	0	0.1688	−3.52	−3.17	−3.53
^{309}119	11.3386	3	0.2282	−1.24	−1.42	−0.57
^{310}119	10.8335	3	0.1829	0.29	−0.10	0.27
^{311}119	10.6003	0	0.1697	−0.26	0.53	0.63
^{312}119	10.4397	2	0.1386	1.17	0.97	0.95
^{313}119	9.4978	2	0.1562	3.61	3.87	4.36
^{314}119	9.1165	1	0.1286	4.98	5.16	4.87
^{315}119	9.3054	1	0.1420	3.95	4.49	4.72
^{316}119	8.7705	2	0.1192	6.50	6.39	6.33
^{317}119	9.2532	3	0.1826	4.55	4.64	5.49
^{318}119	9.1841	0	0.1549	4.23	4.86	4.44
^{319}119	8.4849	6	0.1484	8.17	7.44	10.18
			Nuclei with Z=120			
^{287}120	13.9149	4	0.1680	−5.36	−6.39	−4.79
^{288}120	13.7471	0	0.2526	−6.59	−6.87	−6.67
^{289}120	13.6763	0	0.1661	−6.22	−5.97	−5.32
^{290}120	13.6305	0	0.2470	−6.41	−6.69	−6.49
^{291}120	13.4054	2	0.1639	−5.08	−5.47	−4.57
^{292}120	13.3084	0	0.2505	−5.88	−6.09	−5.90
^{293}120	13.2366	2	0.1701	−4.82	−5.16	−4.27
^{294}120	13.0718	0	0.2382	−5.45	−5.65	−5.47
^{295}120	13.0989	2	0.1648	−4.58	−4.91	−4.03
^{296}120	13.1873	0	0.2326	−5.69	−5.92	−5.74
^{297}120	13.0230	0	0.1621	−5.14	−4.78	−4.20
^{298}120	12.9002	0	0.2271	−5.17	−5.37	−5.19
^{299}120	13.1851	0	0.1633	−5.48	−5.15	−4.55
^{300}120	13.2871	0	0.2420	−5.95	−6.19	−6.01
^{301}120	13.0349	2	0.1736	−4.57	−4.87	−4.00
^{302}120	12.8782	0	0.2369	−5.21	−5.39	−5.22
^{303}120	12.7949	2	0.1737	−4.14	−4.40	−3.55
^{304}120	12.7451	0	0.2371	−4.99	−5.14	−4.98
^{305}120	13.2712	2	0.1827	−5.09	−5.42	−4.53
^{306}120	13.8225	0	0.2446	−6.98	−7.31	−7.14
^{307}120	13.5776	4	0.1861	−5.11	−6.06	−4.49
^{308}120	13.0359	0	0.2652	−5.65	−5.81	−5.65
^{309}120	12.1724	0	0.1994	−3.71	−3.10	−2.60
^{310}120	11.4753	0	0.2312	−2.38	−2.34	−2.20
^{311}120	11.1018	2	0.1802	−0.57	−0.49	0.18
^{312}120	11.0535	0	0.2029	−1.35	−1.29	−1.17
^{313}120	10.9229	2	0.1603	−0.10	−0.04	0.61
^{314}120	9.9714	0	0.2273	1.47	1.73	1.83

Continued on next page

Table 8-continued from previous page

Nuclide	Q_α	l	P_α	$\log_{10} T_{1/2}^{\rm cal}$	$\log_{10} T_{1/2}^{\rm UDL}$	$\log_{10} T_{1/2}^{\rm DZR}$
^{315}120	10.1487	0	0.1807	1.23	2.15	2.42
^{316}120	9.9651	0	0.1873	1.54	1.72	1.81
^{317}120	9.9639	3	0.1513	2.77	2.69	3.50
^{318}120	9.9875	0	0.1785	1.47	1.62	1.71
^{319}120	9.8887	3	0.1454	2.98	2.90	3.70
^{320}120	9.7100	0	0.1861	2.25	2.45	2.53

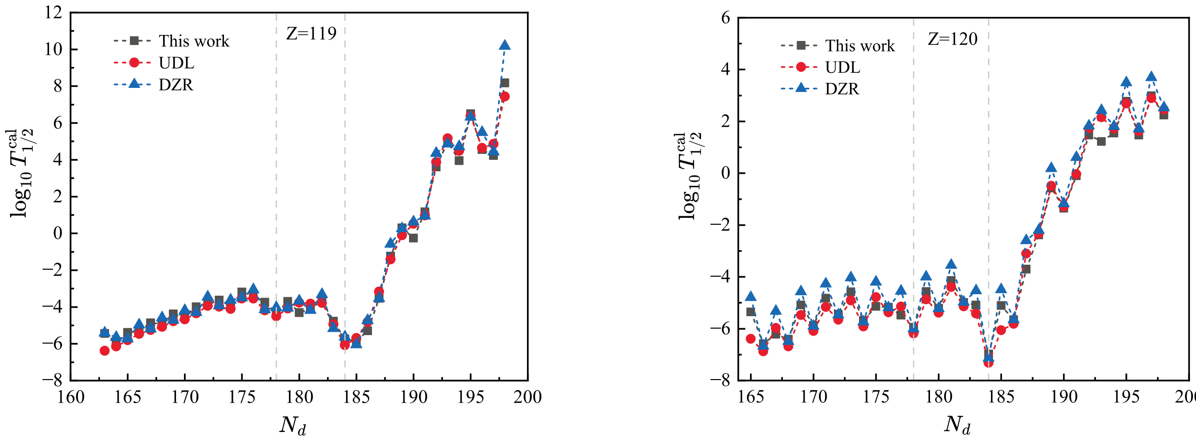

Fig. 5. (color online) Predicted α decay half-lives for the even-even, odd-even, and odd-odd nuclei with $Z = 119$ and 120 are presented in logarithmic form using our model, UDL, and DZR.

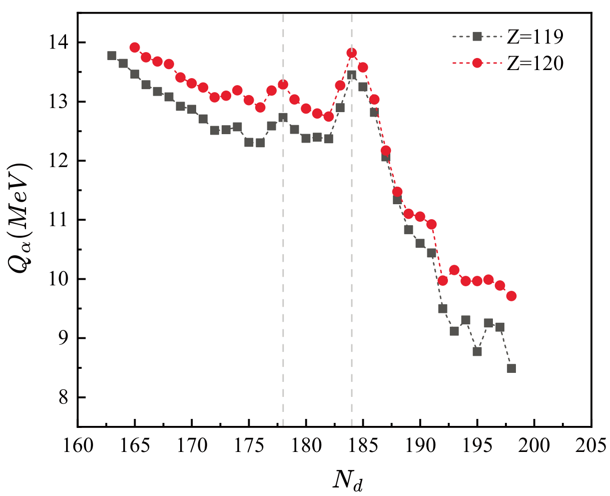

Fig. 6. (color online) Predicted α decay energy of even-even, odd-A, and odd-odd nuclei with $Z = 119$ and 120. Q_α is calculated by WS3+.

However, this variation trend is not obvious in odd-A nuclei with $Z = 120$. When the neutron number is closer to the neutron magic number, the α decay preformation factor is smaller, while it increases as the neutron number deviates further from this magic shell closure [95]. Moreover, during α decay, when the neutron or proton numbers of the corresponding daughter nucleus are magic numbers, the half-life reaches its minimum value [96, 97]. When the neutron number exceeds the neutron magic number by two nucleons, the parent nucleus tends to become stable by emitting an α particle. In this case, the half-life will reach its minimum value. The depth of the minimum value depends on the stability of the daughter nucleus, meaning that the more stable nucleus corresponds to a deeper minimum value. From the above content, we can conclude that $N = 184$ is the possible neutron magic number, while $N = 178$ can be considered the neutron submagic number [97].

IV. SUMMARY

In summary, based on the WKB theory, considering the α decay preformation factors P_α, we systematically investigate the α decay half-lives of 559 nuclei, including 177 even-even, 277 odd-A, and 105 odd-odd nuclei. The α decay preformation factors P_α are calculated using the CFM. The assault frequency ν is analytically parameterized using experimental α decay energies and charge radii of the parent nucleus. For all 559 nuclei taken from NUBASE2020, the standard deviation calculated by our model is 0.408. In addition, we extend this model to predict the α decay half-lives of 70 even-even, odd-A, and odd-odd nuclei with $Z = 119$ and 120 and compare the predicted results with those calculated by

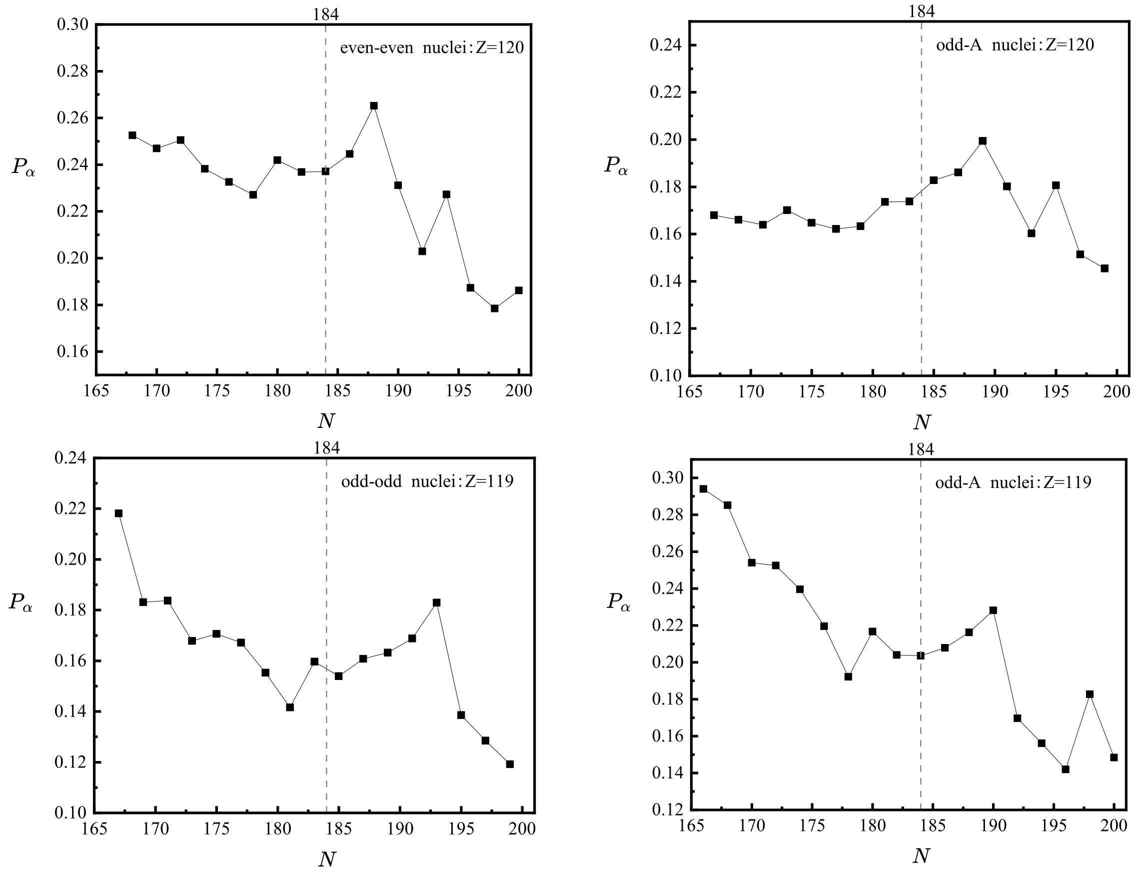

Fig. 7. Predicted α decay preformation factors of even-even, odd-A, and odd-odd nuclei with Z = 119 and 120.

UDL and DZR. The results predicted by these three formulas are consistent in trend, indicating that our model has a certain reliability. The predicted α decay energies and half-lives for isotopes with Z = 119 and 120 exhibit similar behavior at N = 178 and N = 184. Besides, the predicted α decay preformation factors for isotopes with Z = 119 and 120 exhibit similar phenomena at N = 184. These indicate that both 178 and 184 are possible neutron magic and submagic numbers, respectively. The results of this work can provide some information for future experimental studies, such as the synthesis of elements with Z = 119 and 120 and will also prompt inquiries about the nuclear structure.

References

[1] E. Rutherford and H. Geiger, Proc. R. Soc. London A **81**, 162 (1908)

[2] G. Gamow, Z. Phys **51**, 204 (1928)

[3] R. W. Gurney and E. U. Condon, Nature **122**, 439 (1928)

[4] J. Khuyagbaatar, A. Yakushev, C. E. Düllmann *et al.*, Phys. Rev. Lett **112**, 172501 (2014)

[5] R. J. Carroll, R. D. Page, D. T. Joss *et al.*, Phys. Rev. Lett **112**, 092501 (2014)

[6] D. S. Delion, R. J. Liotta, and R. Wyss, Phys. Rev. C **92**, 051301(R) (2015)

[7] D. D. Ni, Z. Z. Ren, T. K. Dong *et al.*, Phys. Rev. C **78**, 044310 (2008)

[8] W. M. Seif, M. Shalaby, and M. F. Alrakshy, Phys. Rev. C **84**, 064608 (2011)

[9] Y. J. Ren and Z. Z. Ren, Phys. Rev. C **85**, 044608 (2012)

[10] J. G. Deng, J. H. Cheng, B. Zheng *et al.*, Chin. Phys. C **41**, 124109 (2017)

[11] H. F. Zhang, G. Royer, Y. J. Wang *et al.*, Phys. Rev. C **80**, 057301 (2009)

[12] S. M. S. Ahmed, R. Yahaya, S. Radiman *et al.*, J. Phys. G: Nucl. Part. Phys. **40**, 065105 (2013)

[13] S. M. S. Ahmed, Nucl. Phys. A **962**, 103 (2017)

[14] X. J. Bao, S. Q. Guo, H. F. Zhang *et al.*, Phys. Rev. C **95**, 034323 (2017)

[15] S. Q. Guo, X. J. Bao, Y. Gao *et al.*, Nucl. Phys. A **934**, 110 (2015)

[16] H. F. Zhang, W. Zuo, J. Q. Li *et al.*, Phys. Rev. C **74**, 017304 (2006)

[17] X. J. Bao, H. F. Zhang, G. Royer *et al.*, Nucl. Phys. A **921**, 85 (2014)

[18] J. M. Dong, W. Zuo, J. Z. Gu *et al.*, Phys. Rev. C **81**, 064309 (2010)

[19] Y. Z. Wang, S. J. Wang, Z. Y. Hou *et al.*, Phys. Rev. C **92**, 064301 (2015)

[20] S. Luo, Y. Y. Xu, D. X. Zhu *et al*., Eur. Phys. J. A **58**, 244 (2022)
[21] S. Luo, X. Pan, J. J. Dong *et al*., Commun. Theor. Phys. **75**, 025301 (2023)
[22] H. M. Liu, J. Y. Xu, J. G. Deng *et al*., Int. J. Mod. Phys. E **28**, 1950089 (2019)
[23] J. H. Cheng, J. L. Chen, J. G. Deng *et al*., Nucl. Phys. A **987**, 350 (2019)
[24] J. G. Deng, J. C. Zhao, J. L. Chen *et al*., Chin. Phys. C **42**, 044102 (2018)
[25] Y. T. Zou, X. Pan, H. M. Liu *et al*., Phys. Scr. **96**, 075301 (2021)
[26] H. F. Gui, H. M. Liu, X. J. Wu *et al*., Commun. Theor. Phys. **74**, 055301 (2022)
[27] Y .T. Oganessian, Radiochim. Acta **99**, 429 (2011)
[28] Z. Y. Zhang, H. B. Yang, M. H. Huang *et al*., Phys. Rev. Lett. **126**, 152502 (2021)
[29] B. Buck, A. C. Merchant, and S. M. Perez, Phys. Rev. C **45**, 2247 (1992)
[30] D. N. Basu, Phys. Lett. B **566**, 90 (2003)
[31] P. R. Chowdhury, C. Samanta, and D. N. Basu, Phys. Rev. C **73**, 014612 (2006)
[32] C. Samanta, P. R. Chowdhury, and D. N. Basu, Nucl. Phys. A **789**, 142 (2007)
[33] P. R. Chowdhury, C. Samanta, and D. N. Basu, Phys. Rev. C **77**, 044603 (2008)
[34] G. Royer, J. Phys. G Nucl. Part. Phys. **26**, 1149 (2000)
[35] H. F. Zhang and G. Royer, Phys. Rev. C **76**, 047304 (2007)
[36] J. M. Dong, H. F. Zhang, Y. Z. Wang *et al*., Nucl. Phys. A **832**, 198 (2010)
[37] K. Varga, R. G. Lovas, and R. J. Liotta, Phys. Rev. Lett. **69**, 37 (1992)
[38] B. Buck, A. C. Merchant, and S. M. Perez, At. Data Nucl. Data Tables **54**, 53 (1993)
[39] Y. Y. Xu, H. M. Liu, D. X. Zhu *et al*., Eur. Phys. J. A **58**, 16 (2022)
[40] H. Geiger. Ph. D. and J. M. Nuttall B. Sc., Phil. Mag. **22**, 613 (1911)
[41] B. A. Brown, Phys. Rev. C **46**, 811 (1992)
[42] C. Qi, F. R. Xu, R. J. Liotta *et al*., Phys. Rev. Lett. **103**, 072501 (2009)
[43] C. Qi, F. R. Xu, R. J. Liotta *et al*., Phys. Rev. C **80**, 044326 (2009)
[44] G. Royer, Nucl. Phys. A **848**, 279 (2010)
[45] J. G. Deng, H. F. Zhang, and G. Royer, Phys. Rev. C **101**, 034307 (2020)
[46] V. E. Viola Jr, G. T. Seaborg, J. Inorg. Nucl. Chem. **28**, 741 (1966)
[47] A. Sobiczewski, Z. Patyk, and S. Ćwiok, Phys. Lett. B **224**, 1 (1989)
[48] D. T. Akrawy and A. H. Ahmed, Phys. Rev. C **100**, 044618 (2019)
[49] Y. Hatsukawa, H. Nakahara, and D. C. Hoffman, Phys. Rev. C **42**, 674 (1990)
[50] D. N. Poenaru, M. Ivascu, A. Sndulescu *et al*., Phys. Rev. C **32**, 572 (1985)
[51] D. N. Poenaru, R. A. Gherghescu, and W. Greiner, Phys. Rev. Lett. **107**, 062503 (2011)
[52] D. N. Poenaru, R. A. Gherghescu, and W. Greiner, Phys. Rev. C **85**, 034615 (2012)
[53] S. A. Gurvitz and G. Kalbermann, Phys. Rev. Lett. **59**, 262 (1987)
[54] S. A. Gurvitz, P. B. Semmes, W. Nazarewicz *et al*., Phys. Rev. A **69**, 042705 (2004)
[55] X. D. Sun, C. Duan, J. G. Deng *et al*., Phys. Rev. C **95**, 014319 (2017)
[56] R. Moustabchir and G. Royer, Nucl. Phys. A **683**, 266 (2001)
[57] Z. Z. Ren, C. Xu, and Z. J. Wang, Phys. Rev. C **70**, 034304 (2004)
[58] G. Dodig-Crnković, F. A. Janouch, R. J. Liotta *et al*., Nucl. Phys. A **444**, 419 (1985)
[59] I. Tonozuka and A. Arima, Nucl. Phys. A **323**, 45 (1979)
[60] K. Varga, R. G. Lovas, and R. J. Liotta, Nucl. Phys. A **550**, 421 (1992)
[61] C. Xu, Z. Z. Ren, G. Röpke *et al*., Phys. Rev. C **93**, 011306 (2016)
[62] C. Xu and Z. Z. Ren, Nucl. Phys. A **760**, 303 (2005)
[63] H. F. Zhang, G. Royer, and J. Q. Li, Phys. Rev. C **84**, 027303 (2011)
[64] G. L. Zhang, X. Y. Le, and H. Q. Zhang, Phys. Rev. C **80**, 064325 (2009)
[65] Y. B. Qian and Z. Z. Ren, Sci. China Phys. Mech. Astron. **56**, 1520 (2013)
[66] S. M. S. Ahmed, R. Yahaya, and S. Radiman, Rom. Rep. Phys. **65**, 1281 (2013)
[67] J. G. Deng, J. C. Zhao, P. C. Chu *et al*., Phys. Rev. C **97**, 044322 (2018)
[68] D. M. Deng, Z. Z. Ren, D. D. Ni *et al*., J. Phys. G: Nucl. Part. Phys. **42**, 075106 (2015)
[69] D. M. Deng and Z. Z. Ren, Phys. Rev. C **93**, 044326 (2016)
[70] D. F. Rojas-Gamboa, J. E. Perez Velasquez, N. G. Kelkar *et al*., Phys. Rev. C **105**, 034311 (2022)
[71] J. E. Perez Velasquez, N. G. Kelkar, and N. J. Upadhyay, Phys. Rev. C **99**, 024308 (2019)
[72] J. P. Cui, Y. H. Gao, Y. Z. Wang *et al*., Nucl. Phys. A **1017**, 122341 (2022)
[73] Z. Q. Sheng, G. W. Fan, and J. F. Qian, Acta Phys. Sin. **64**, 112101 (2015)
[74] R. Hofstadter, Annu. Rev. Nucl. Sci. **7**, 231 (1957)
[75] A. Soylu and C. Qi, Nucl. Phys. A **1013**, 122221 (2021)
[76] Y. B. Qian and Z. Z. Ren, Nucl. Phys. A **852**, 82 (2011)
[77] Y. B. Qian, Z. Z. Ren, and D. D. Ni, Nucl. Phys. A **866**, 1 (2011)
[78] Y. B. Qian and Z. Z. Ren, Phys. Rev. C **85**, 027306 (2012)
[79] F. G. Kondev, M. Wang, W. J. Huang *et al*., Chin. Phys. C **45**, 030001 (2021)
[80] M. Wang, W. J. Huang, F. G. Kondev *et al*., Chin. Phys. C **45**, 030003 (2022)
[81] W. J. Huang, M. Wang, F. G. Kondev *et al*., Chin. Phys. C **45**, 030002 (2021)
[82] A. Insolia, P. Curutchet, R. J. Liotta *et al*., Phys. Rev. C **44**, 545 (1991)
[83] M. Ismail, W. M. Seif, A. Adel *et al*., Nucl. Phys. A **958**, 202 (2017)
[84] P. Möller, J. R. Nix, W. D. Myers *et al*., At. Data Nucl. Data Tables **59**, 185 (1995)
[85] J. Duflo and A. P. Zuker, Phys. Rev. C **52**, R23 (1995)
[86] R. C. Nayak and L. Satpathy, At. Data Nucl. Data Tables **98**, 616 (2012)
[87] N. Wang and M. Liu, Phys. Phys. C **84**, 051303 (2011)
[88] N. Wang, M. Liu, X. Z. Wu *et al*., Phys. Phys. C **93**, 014302 (2016)
[89] N. Wang, M. Liu, X. Z. Wu *et al*., Phys. Lett. B **734**, 215 (2014)
[90] I. Muntian, Z. Patyk, and A. Sobiczewski, Acta Phys. Pol. B

32, 691 (2001)
[91] A. Sobiczewski and K. Pomorski, Prog. Part. Nucl. Phys. **58**, 292 (2007)
[92] A. N. Kuzmina, G. G. Adamian, N. V. Antonenko *et al*., Phys. Rev. C **85**, 014319 (2012)
[93] S. Goriely, N. Chamel, and J. M. Pearson, Phys. Rev. C **93**, 034337 (2016)
[94] S. Liran, A. Marinov, and N. Zeldes, Phys. Rev. C **62**, 047301 (2000)
[95] J. G. Deng and H. F. Zhang, Phys. Rev. C **102**, 044314 (2020)
[96] N. G. Kelkar and M. Nowakowski, J. Phys. G: Nucl. Part. Phys. **43**, 105102 (2016)
[97] Z. S. Ge, C. Li, J. J. Li *et al*., Phys. Rev. C **98**, 034312 (2018)
[98] https://t2.lanl.gov/nis/data/astro/molnix96/spidat.html