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Predictions on properties of α decay and spontaneous fission in superheavy odd-Z nuclei

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We systematically investigate the competition between α decay and spontaneous fission in the region of superheavy odd-Z nuclei up to $Z = 121$. The heavier cluster emissions are somewhat of interest for these superheavy nuclei (SHN) as well. In detail, on the basis of the density-dependent cluster model, the deformed α-core potential is obtained from the double-folding integral. The α-decay half-lives of involved nuclei are then achieved within the improved two-potential approach. On the other hand, the spontaneous fission half-lives are given by the employed formula related to the fissility parameter and the fission barrier height. It is interesting that the decay characteristic of studied nuclei is discussed with varying of the Z and N numbers to some extent, including the tentative detection on the "island of stability." The present results can be expected to be useful in the future experiment particularly for the unknown elements 119 and 121, namely the identification of synthesized SHN.

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I. INTRODUCTION

In the pursuit of the border of the elements' existence, heaviest nuclei have received special attention for a long time in physics and even chemistry. It is of chemical interest to seek the exotic or similar properties of superheavy nuclei as compared with their chemical homologs [1]. Physically, nuclei beyond $Z \approx 106$ are initially supposed to be unstable with an increase of the atomic number according to the nuclear liquid-drop model [2]. Owing to the strong influence of spherical and deformed shell effect, superheavy nuclei and even these nuclei along with very long lifetimes forming the "island of stability" are expected to be observed [1]. The detection on the existence of heavier elements in natural samples has been sequentially made from then on [3–5]. To date, the synthesis and identification of superheavy isotopes is an attractive and hot topic in contemporary nuclear physics. With the enormous development of experimental technologies and facilities, significant progress in this subject was achieved during the last 30 years using the "cold" [6,7] and "hot" [8] fusion reactions. The experimental investigations are mainly performed in these places (see Refs [6–18] and references cited therein): the Lawrence Berkeley National Laboratory in Berkeley (USA), the Flerov Laboratory of Nuclear Reactions (FLNR) of Joint Institute for Nuclear Research (JINR) in Dubna (Russia) involving the cooperation with the researchers from the Lawrence Livermore National Laboratory, GSI Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt (Germany), and the Institute of Physical and Chemical Research (RIKEN) in Saitama (Japan), etc.

After more than half-year irradiation of a ^{209}Bi target with a ^{70}Zn beam, the heaviest nucleus $^{278}113$ in the cold fusion reaction was formed [7]. The heaviest element, 118, was synthesized in the ^{48}Ca induced hot fusion [8,11,13]. Recently, the final gap to $Z = 118$ in the nuclide chart was filled by the production of the new superheavy element 117 in the similar fusion reaction but with the radioactive ^{249}Bk targets [12–14]. Very strikingly, the existence of the new element 117 was exactly reconfirmed in the very recent experiment, marking the official status of the new element [15]. Further progress in the search for new elements with $Z > 118$ was given special attention from both the experimental and theoretical sides [19–22]. Very impressively, these newly synthesized elements and new isotopes are mainly identified by the sequential α-decay chain from unknown nuclei to known nuclei, usually ending with spontaneous fission. As the dominant decay modes of SHN, α decay and spontaneous fission can be considered as the limiting factor that determines the stability of heaviest nuclei. Based on applicable models such as the shell model, the cluster model, and the fissionlike model, extensive theoretical studies have been performed to obtain the α-decay half-lives in the whole nuclide chart especially the superheavy mass region [23–47]. Among these studies, Denisov *et al.* proposed a united model for α decay and α capture [29,38], Delion and Liotta recently proposed a new representation of shell model to depict α emission [32], Royer *et al.* generalized a liquid drop model to treat α emission as a spontaneous asymmetric fission [34], and Santhosh *et al.* described the α-decay process within the Coulomb and proximity potential model for deformed nuclei [40]. Systematics of α-decay half-lives was also investigated in semiclassical relations including some important ingredients such as shell effects [24–26,48]. In our group, a unified formula was provided for half-lives of α decay and cluster radioactivity [49] and a new Geiger-Nuttall law of α decay was recently revealed by considering the effects of quantum numbers [37]. In spite of sharing a similar physical mechanism, the situation of spontaneous fission is quite more difficult because

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of the existing large uncertainties in the process [43]. The full microscopic understanding of such a multidimensional problem appears to be quite difficult especially for superheavy nuclei. In addition, the concept of cluster radioactivity (CR) was changed by allowing the emissions with $Z_c > 28$ from superheavy parents [50], implying the possible contest of CR with α decay and spontaneous fission in the SHN.

Compared with the theoretical α-decay studies of even-Z nuclei, those of odd-Z nuclei seem to be rare [35,36,40,41]. It is exciting that a long-lived α-decaying nucleus ^{270}Db was populated in the confirmed α-decay chain from ^{294}117 [15]. Encouraged by our previous works on α-decay half-lives of superheavy nuclei, we aim at not only extending the study to the large region of odd-Z heaviest nuclei, but also probing into the general trend of half-lives of unknown heaviest nuclei and even the possible location of the "island of stability" for SHN in the nuclide chart. The half-lives of both α decay and spontaneous fission are systematically investigated for these odd-Z nuclei in this paper. As well, the cluster radioactivity of SHN is somewhat discussed and of interest. Combining the present calculations, sequential information on the contest of α decay and spontaneous fission is provided in the pursuit of being useful for future experiments, especially the unknown elements beyond $Z = 118$ such as superheavy elements 119 and 121. This article is organized in the following way. Section II briefly shows the key points of the formalism on calculating α decay and spontaneous fission half-lives. In Sec. III, numerical results and corresponding discussions are presented, including the tentative detections on cluster radioactivity of superheavy nuclei. A summary is given in Sec. IV.

II. THEORETICAL FRAMEWORK

Given that an α particle interacts with an axially symmetric deformed daughter nucleus, the total interaction potential of the α-core system, consisting of the nuclear and Coulomb components, is given by

$$V(r,\theta) = \lambda V_N(r,\theta) + V_C(r,\theta), \tag{1}$$

where λ is the renormalization factor for nuclear potential, and θ is the orientation angle of the emitted α particle with respect to the symmetric axis of the daughter nucleus. Within the density-dependent cluster model, the nuclear and Coulomb potentials are microscopically constructed by the double-folding integral,

$$V_{N\,\mathrm{or}\,C}(\mathbf{r},\theta) = \iint d\mathbf{r}_1 d\mathbf{r}_2 \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)\upsilon(\mathbf{s} = |\mathbf{r}_2 + \mathbf{r} - \mathbf{r}_1|), \tag{2}$$

where $\upsilon(\mathbf{s})$ denotes the M3Y-Reid-type nucleon-nucleon interaction and standard Coulomb proton-proton interaction for the nuclear potential and the Coulomb potential, respectively. In addition to the usually used Gaussian density distribution of the spherical α particle ρ_1, the density distribution ρ_2 of the core nucleus is depicted in a deformed Fermi formula,

$$\rho_2(r_2,\theta_1) = \frac{\rho_0}{1 + \exp\left[\frac{r_2 - R_0[1+\beta_2 Y_{20}(\theta_1)+\beta_4 Y_{40}(\theta_1)]}{a}\right]}, \tag{3}$$

where the ρ_0 value is determined by integrating the density distribution equivalent to the mass or atomic numbers of the corresponding daughter nucleus (respectively, for the nuclear and Coulomb potentials). $R_0 = 1.07 A_d^{1/3}$ fm, $a = 0.54$ fm, and β_2 and β_4 are, respectively, the quadrupole and hexadecapole deformation parameters of the daughter nucleus, which are taken from the theoretical values [51,52]. The details on the double-folding process can be found in Refs. [35,43,53,54] and references therein. Subsequently, considering one certain orientation angle θ, the total potential $V(r,\theta)$ is reduced into the case $V(r)$. Under the two-potential treatment [28], the potential $V(r)$ is then divided into two parts: the "inner" term and the "outer" term by a separation radius R which is taken reasonably inside the potential barrier. The Schrödinger equation is numerically solved in the inner potential $U(r)$ to get the bound state wave function $\phi_0(r)$, which exponentially vanishes from the separation radius R [46]. In the above procedure, the depth λ is adjusted for each decay to reproduce the decay energy Q, and satisfy the Wildermuth condition which contains the main effect of the Pauli principle [55]. One can then obtain the α-decay width $\Gamma(\theta)$ for the given angle θ,

$$\Gamma(\theta) = \frac{\hbar^2 k}{\mu}\left[\frac{\phi_0(\bar{r})}{G_\ell(k\bar{r})}\right]^2, \tag{4}$$

in view of the modified two-potential approach [28]. Here $k = \sqrt{2\mu Q}/\hbar$, and G_ℓ is the irregular Coulomb wave function. Additionally, the favored α decays ($\ell = 0$) are considered in the present work. The value of $\bar{r}$ is chosen well in such a way that the potential V can be well approximated by the repulsive part (or say the nuclear attractive part disregards) for $r \geqslant \bar{r}$. In detail, the large enough $\bar{r}$ should be located between the barrier radius and the separation radius R, and it is closer to the former one than to R. It is to be noted that the decay width $\Gamma(\theta)$ does not depend on the particular choice of R or $\bar{r}$ (see details in Refs. [28,46]). Ultimately, the final decay width is given by averaging $\Gamma(\theta)$ in all directions [29,35,38,44],

$$\Gamma = \int_0^{\pi/2} \Gamma(\theta)\sin(\theta)d\theta. \tag{5}$$

The α-decay half-life is then related with the decay width as

$$T_{1/2} = \frac{\hbar \ln 2}{P_\alpha \Gamma}, \tag{6}$$

TABLE I. Comparison of our present calculated results with those from the MCCM within the coupled channels approach and the corresponding measured values, for the even-even Fm isotopes. As can be seen, the results of this study (column 4) are coherent with those of the MCCM [36].

Transition	Q_α(MeV)	T_α^{expt} (s)	T_α^{calc} (s)	T_α^{MCCM} (s)[36]
^{246}Fm→^{242}Cf	8.373	1.49×10^0	1.84×10^0	2.57×10^0
^{248}Fm→^{244}Cf	7.999	4.84×10^1	3.10×10^1	4.29×10^1
^{250}Fm→^{246}Cf	7.557	2.65×10^3	1.30×10^3	1.59×10^3
^{252}Fm→^{248}Cf	7.153	1.09×10^5	5.32×10^4	6.08×10^4
^{254}Fm→^{250}Cf	7.307	1.37×10^4	1.12×10^4	1.25×10^4
^{256}Fm→^{252}Cf	7.027	1.35×10^5	1.68×10^5	1.58×10^5

TABLE II. Comparison of the computed results with the available data from the recent experiment at Dubna [14] for α decay chains originating from element 117. T_α^{calc} is obtained in the present framework, and the SF half-lives in the last column is taken from Eq. (7).

Nucleus	Q_α(MeV)	T_α^{expt}	T_α^{calc}	T_α^{UD}	T_α^{VS}	T_{SF}
$^{294}117$	10.96-11.12	50^{+60}_{-18} ms	113-44 ms	68-27 ms	50-19 ms	5.75 d
$^{293}117$	10.75-11.36	22^{+8}_{-4} ms	268-8 ms	661-20 ms	810-23 ms	3.99 d
$^{290}115$	9.92-10.42	$0.24^{+0.28}_{-0.09}$ s	18.68-0.70 s	97.73-3.87 s	84.14-3.14 s	267.71 d
$^{289}115$	10.29-10.69	$0.33^{+0.12}_{-0.08}$ s	1.04-0.09 s	2.45-0.22 s	3.27-0.28 s	80.71 d
$^{286}113$	9.75-9.89	13^{+12}_{-4} s	11-4 s	65-26 s	59-23 s	3.86 d
$^{285}113$	9.60-10.32	$4.2^{+1.4}_{-0.8}$ s	19.3-0.2 s	47.6-0.5 s	70.7-0.6 s	20.33 h
^{282}Rg	9.14±0.05	59^{+55}_{-19} s	218-103 s	1307-629 s	1295-616 s	4.13 min
^{281}Rg	9.41±0.05	170^{+60}_{-30} s	17.4-8.5 s	52.2-25.9 s	81.1-39.8 s	32.01 s
^{278}Mt	9.52-9.69	$5.2^{+6.2}_{-1.8}$ s	1.7-0.5 s	13.6-4.4 s	12.9-4.1 s	6.29 s
^{274}Bh	8.89±0.05	54^{+65}_{-19} s	38-18 s	312-150 s	320-152 s	30.09 min

where P_α represents the preformation probability of the α particle in the parent nucleus. As in previous systematic studies [46,47], this indispensable quantity is taken as a same constant for one kind of nuclei, i.e., $P_\alpha^{e-e} = 0.38$, $P_\alpha^{\mathrm{odd}-A} = 0.27$, and $P_\alpha^{o-o} = 0.17$. This is consistent with the detailed experimental analysis of (n,α) and (p,α) reactions and α activity of even-even nuclei [56], and other α-decay studies [27,30,35,36], and the values are compatible with the microscopic calculation [23]. It should be better for calculating α-decay half-lives if the preformation factor is considered to vary with different parent nuclei instead of a constant [44,45,57]. This is worth further investigation. The above description is the framework of the modified two-potential approach for deformed nuclei within the density-dependent cluster model.

Before we present the detailed results, it is interesting to analyze the validity of the present approach. It is known that the multichannel cluster model (MCCM) [36], based on the successful coupled channels approach, can well reproduce α-decay half-lives and branching ratios for various daughter states, especially the branching ratios for highly excited states. We take the even-even Fm isotopes as an example to perform the comparison of our calculated results with those from the MCCM, as shown in Table I. The first column denotes the α transitions from ground states to ground states, and the following two columns, respectively, list the experimental decay energies and half-lives. The calculated results in the present framework and the MCCM are given in the last two columns. For the calculation of α-decay half-lives, the theoretical values

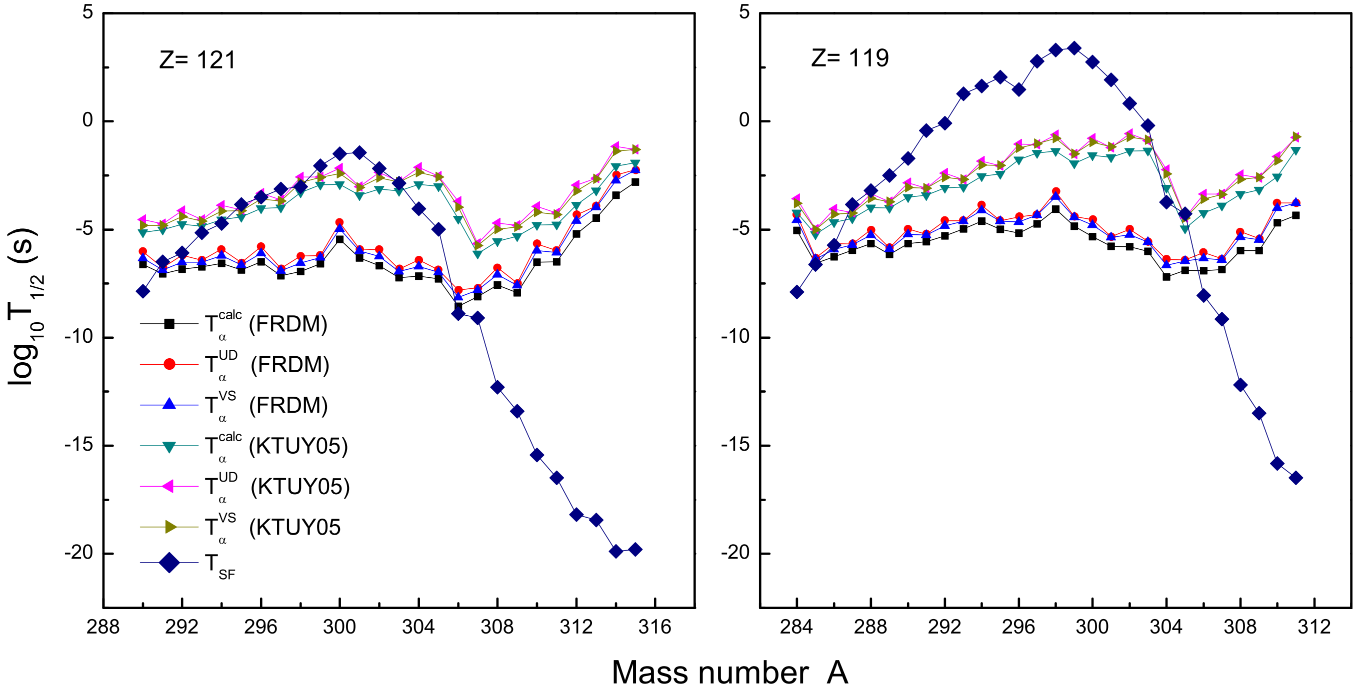

FIG. 1. (Color online) Comparison of the calculated α-decay half-lives with the spontaneous fission half-lives for isotopes of superheavy elements 121 and 119. For each mass (FRDM or KTUY05), three calculated α-decay half-lives, namely these superscripts "calc," "VS," and "UD," are obtained in the present framework, Eqs. (8) and (9).

are usually found to agree with the experimental data within a mean factor of about 2–3 (200%–300%). In addition to the good agreement between theory and experiment, one can see from Table I that the deviations between our results and those of the MCCM, denoted as $\frac{|T_\alpha^{\rm MCCM}-T_\alpha^{\rm calc}|}{T_\alpha^{\rm MCCM}} \times 100\%$, are about in the range of 6%–30%, implying the consistency of the results from these two approaches. Here we mainly focus on the calculations of α-decay half-lives, and the MCCM needs to take large computer time especially for the complicated cases of odd-A and odd-odd nuclei (studied in this work). With the above in mind, the present approach can be used as the reasonable and convenient evaluations of α-decay half-lives for superheavy nuclei.

To identify the decay mode of these studied isotopes of superheavy elements, the spontaneous fission (SF) half-lives are needed to be taken into account. The multidimensional potential energy surface as well as the knowledge of the collective inertia parameters are required for the accurate determination of the SF half-life. Given the complicated problem, the analysis can only be performed in a somewhat restricted region of the nuclide chart because of the large computer time [58]. In addition, phenomenological methods were performed to evaluate the SF half-lives [43,58,59]. For the sake of the preliminary and reasonable estimation about the SF half-lives of SHN, we apply the empirical expression given by Karpov *et al.* [58],

$$\log_{10} T_{1/2}^{\rm SF} = 1146.44 - 75.3153Z^2/A + 1.63792(Z^2/A)^2 - 0.0119827(Z^2/A)^3 + B_f(7.23613 - 0.0947022Z^2/A) + \begin{cases} 0, & \text{even-even nuclei} \\ 1.53897, & \text{odd-A nuclei} \\ 0.80822, & \text{odd-odd nuclei} \end{cases}, \quad (7)$$

which is connected with the fissility parameter and the important fission barrier height on the potential energy surface. The fission barrier is obtained as the sum of the liquid drop barrier and the ground-state shell correction [58,60], i.e., $B_f = B_f^{\rm LDM} + \delta U_{\rm g.s.}$. This formula Eq. (7) can reproduce the general trend of the SF half-life and have a similar behavior with the dynamical predictions, and is expected to be suitable for the superheavy mass region [58].

III. CALCULATED RESULTS AND DISCUSSION

In the present study, we mainly focus on a number of heaviest odd-Z isotopes beyond the element Cf in pursuit of offering valuable information for the future experiment to some extent. In addition to the above framework, we also employ the phenomenological curve of α-decay half-lives for

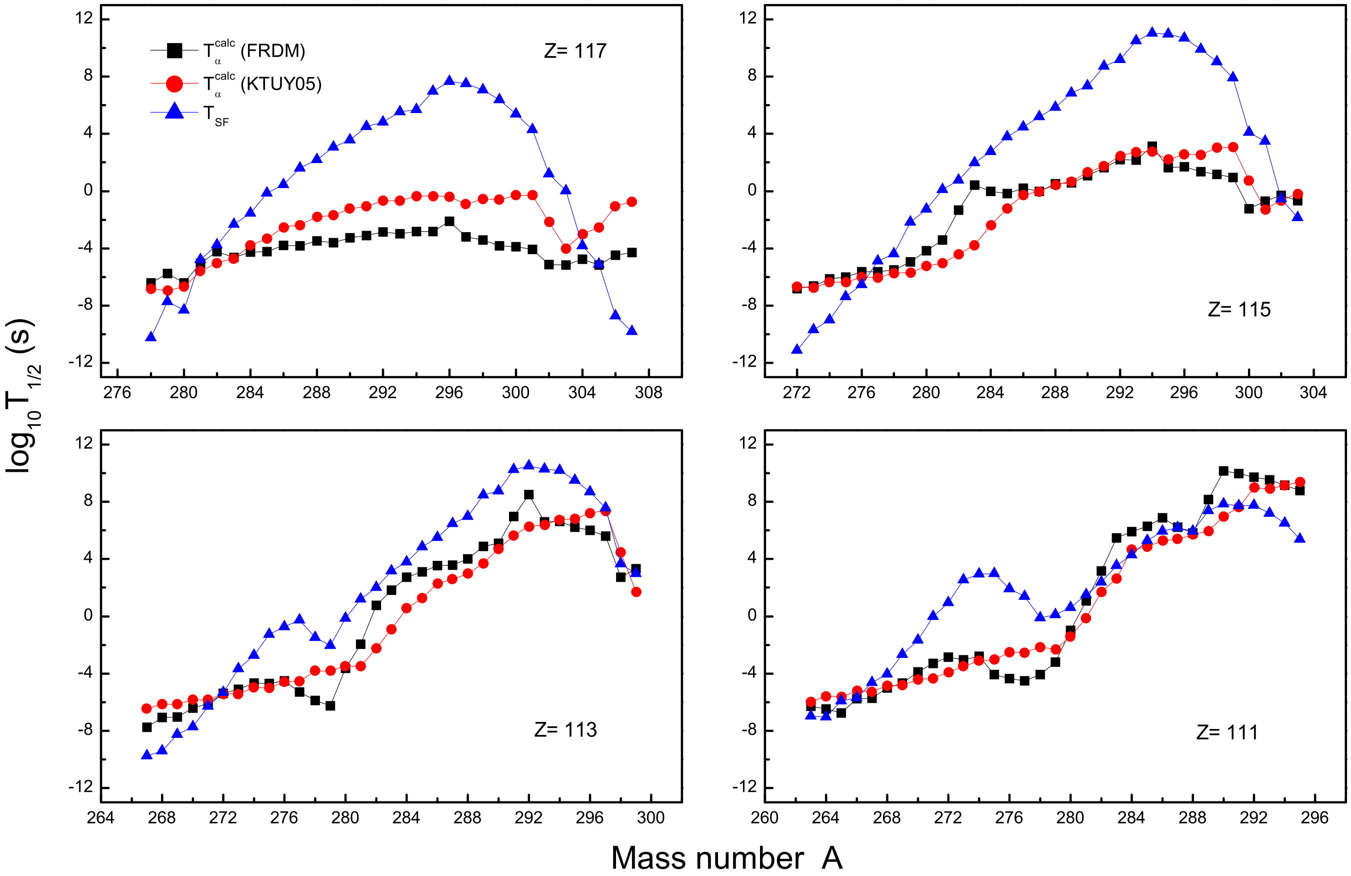

FIG. 2. (Color online) Comparison of calculated α-decay half-lives in the present model with the corresponding SF half-lives for isotopes of superheavy elements 117, 115, 113, and Rg, not including the available experimental data listed in Table II.

comparison. On one hand, the well-known Viola-Seaborg (VS) formula [48],

$$\log_{10} T_{1/2} = (1.66175Z - 8.5166)Q^{-1/2} - 0.20228Z - 33.9069 + h, \tag{8}$$

is used, where Z means the atomic number of the parent nucleus. The hindrance factor h is 0, 1.066, 0.772, and 1.114, respectively, for even-even, even-odd, odd-even, and odd-odd nuclei. On the other hand, a unified description (UD) for α decay and cluster radioactivity half-lives from the previous work of our group is given as [49]

$$\log_{10} T_{1/2} = 0.39961\sqrt{\mu} Z_c Z_d Q^{-1/2} - 1.31008\sqrt{\mu}(Z_c Z_d)^{1/2} + a. \tag{9}$$

The subscripts "d" and "c," respectively, indicate the residual daughter nucleus and the emitted cluster. The last a value is fixed as: $a_{e-e} = -17.00698$, $a_{e-o} = -16.26029$, $a_{o-e} = -16.40484$, and $a_{o-o} = -15.85337$ for the case of α decay. The discrepancies among these h or a values for the different kind of nuclei may come from the block effect of odd protons and odd neutrons. The crucial decay energy released in the cluster (α particle or heavier cluster) transitions between the ground states of parent and corresponding daughter nuclei is obtained as

$$Q = M_p - (M_d + M_c) + k\left(Z_p^{\epsilon} - Z_d^{\epsilon}\right), \tag{10}$$

where M_p, M_d, and M_c are the mass excess of parent and daughter nuclei and emitted clusters, respectively. We use two calculated mass tables, i.e., the finite-range droplet model (FRDM) [51] and the Koura-Tachibana-Uno-Yamada model in 2005 (KTUY05) [52], which are widely used and tested to theoretically calculate masses of nuclei. Moreover, the term $k(Z_p^{\epsilon} - Z_d^{\epsilon})$ is introduced to involve the influence of the atomic electrons on decay energy [38–40], where $k = 8.7$ eV and $\epsilon = 2.517$ for nuclei with $Z \geqslant 60$ and $k = 13.6$ eV and $\epsilon = 2.408$ for nuclei with $Z < 60$. By combing the UD formula Eq. (9) of half-lives for α decay and cluster radioactivity with the two masses FRDM and KTUY05, we initially attempt to consider the possible heavier cluster decay from these studied superheavy nuclei to their daughter nuclei, i.e., the double magic nucleus ^{208}Pb or its neighboring nuclei. It is found that the half-lives of cluster decay for them are generally larger than 10^{30} s ($T_c > 10^{30}$ s), which are quite larger than the corresponding half-lives of both α decay and spontaneous fission. For example, the minimum T_c value (in seconds) of 121, 119, and 117 isotopes are 1.53×10^{32}, 1.93

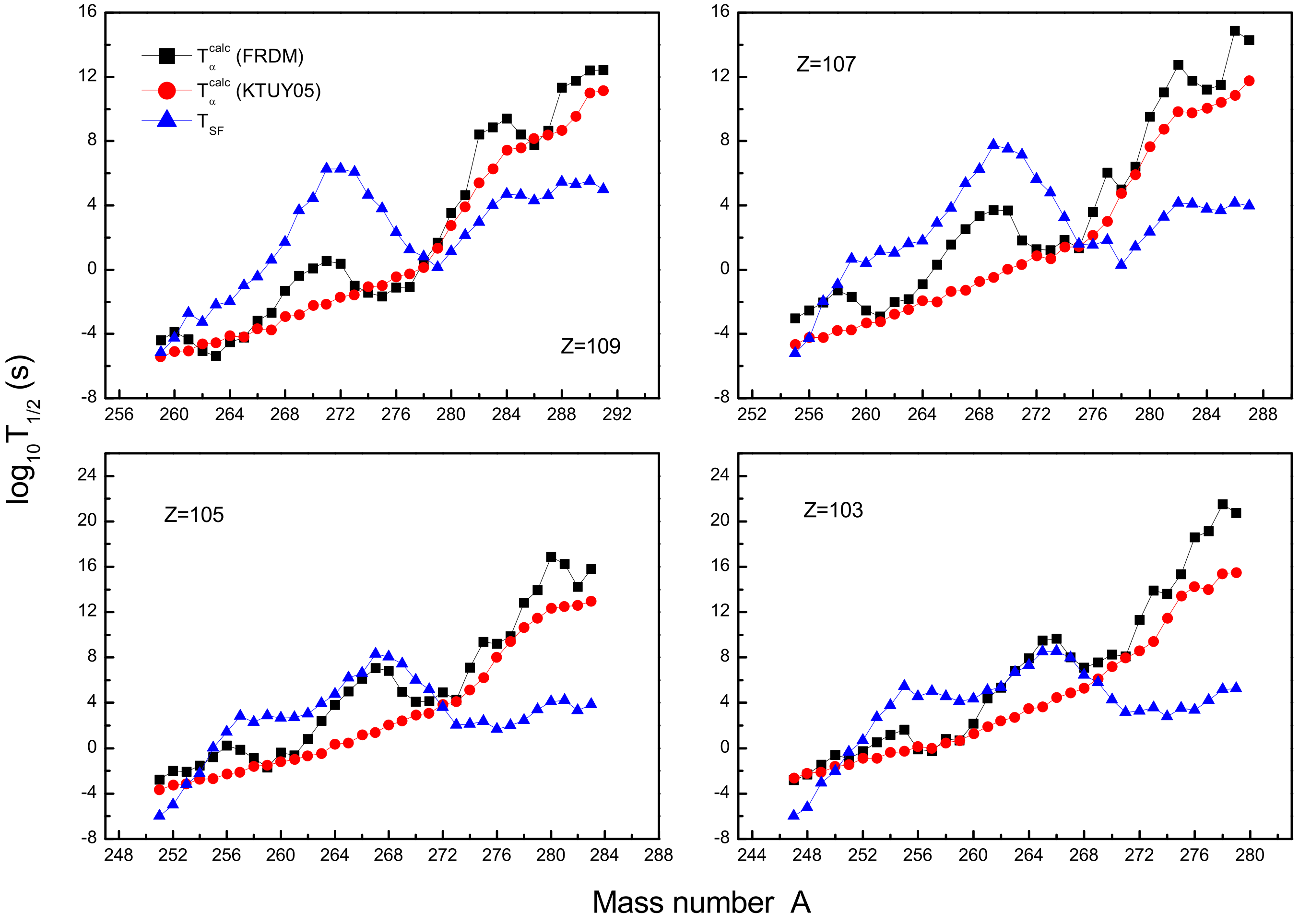

FIG. 3. (Color online) Comparison of calculated α-decay half-lives in the present model with the corresponding SF half-lives for Mt, Bh, Db, and Lr isotopes.

$\times\,10^{33}$, and 2.94 $\times 10^{33}$, respectively, for ^{87}Rb emission from ^{297}121, ^{85}Br emission from ^{295}119, and ^{85}Br emission from ^{293}117 within the FRDM; 3.63 $\times 10^{30}$, 4.99 $\times 10^{30}$, and 1.16 $\times 10^{30}$, respectively, for ^{87}Rb emission from ^{297}121, ^{87}Rb emission from ^{295}119, and ^{85}Br emission from ^{293}117 within the KTUY05. This may imply that the decay channel of cluster radioactivity is not competitive as compared with that of α decay and spontaneous fission for these focused odd-Z nuclei. Consequently, the estimated half-lives of cluster decay have not been included in the following presentation.

By performing the above procedures, we have separately investigated the recent data in the experiment at Dubna [14] of α-decay chains from ^{293,294}117, which can be considered as the further test of the current theoretical framework. Because of the limited knowledge of the level schemes in the superheavy mass region, the angular momentum of the emitted α particle is assumed as zero, which is identical to the choice of Refs. [22,26,40,46,47]. The details on the comparison of the calculated results with the experimental data are listed in Table II. The first column lists the parent nucleus, and the experimental α-decay energies and half-lives are shown in the second and third columns, respectively. The calculated α-decay half-lives in the present model, and the evaluated values in the UD and VS formulas are in order indicated in the following three columns. It is found that the three results are in general consistent with each other. In addition, the estimated SF half-lives by Eq. (7) are denoted in the last column, to perform the competition between α decay and spontaneous fission. It should be noted that these SF half-lives are generally larger than the corresponding α-decay ones. This indicates that the dominant decay mode of these nuclei is α decay, which is consistent with the experimental observation [12–14]. Additionally, the evaluated value for SF of ^{281}Rg in Eq. (7) is 32.01 s, which is close to the experimental one $T_{sf}^{\rm expt} = 18.9^{+6.7}_{-3.3}$ s. As one can see from the table, the present calculated α-decay half-lives well agree with the corresponding measured values.

The pursuit is then extended to the heaviest isotopes of odd-Z elements in the region of $99 \leqslant Z \leqslant 121$. To gain a better insight into the match of α decay and spontaneous fission in these isotopes under study, the logarithm of the α decay and SF half-lives is plotted versus the mass number for each isotopic chain in Figs. 1–4. Based on each mass table such as FRDM or KTUY05, the calculated α-decay half-lives for the isotopic chains of elements 121 and 119, gotten by the present framework, UD and VS expressions, are all displayed in Fig. 1. The SF half-lives from Eq. (7) are given as well for comparison. Obviously, these isotopes with large enough mass number will not survive fission. In the smaller mass region of these isotopes of $Z = 121$ (about $290 < A < 306$) and 119 (about $286 < A < 306$), α decay can be considered as the main mode of decay. It is different that the half-life of spontaneous fission is comparable with that of α decay for $^{294-304}$121 with the KTUY05 masses. The slightly abrupt change of T_α in the region around ^{307}121 and ^{305}119 should be caused by the effect of the $N = 184$ neutron shell. Moreover, considering that the synthesis of $^{299-x}$119 is a hot topic in the pursuit of new elements [20], we separately give the detailed results of $^{299-290}$119 in Table III. The decay mode listed in the last column is determined by comparing the α-decay half-lives with the SF ones. It is obvious that these isotopes prefer to decay via α transitions, and they are also expected to survive with a long enough time above the experimental limitation (about 1 μs) [22,58].

As can be seen from Fig. 1, $T_\alpha^{\rm calc}$, $T_\alpha^{\rm UD}$, and $T_\alpha^{\rm VS}$ are actually close to each other for one kind of Q_α value from

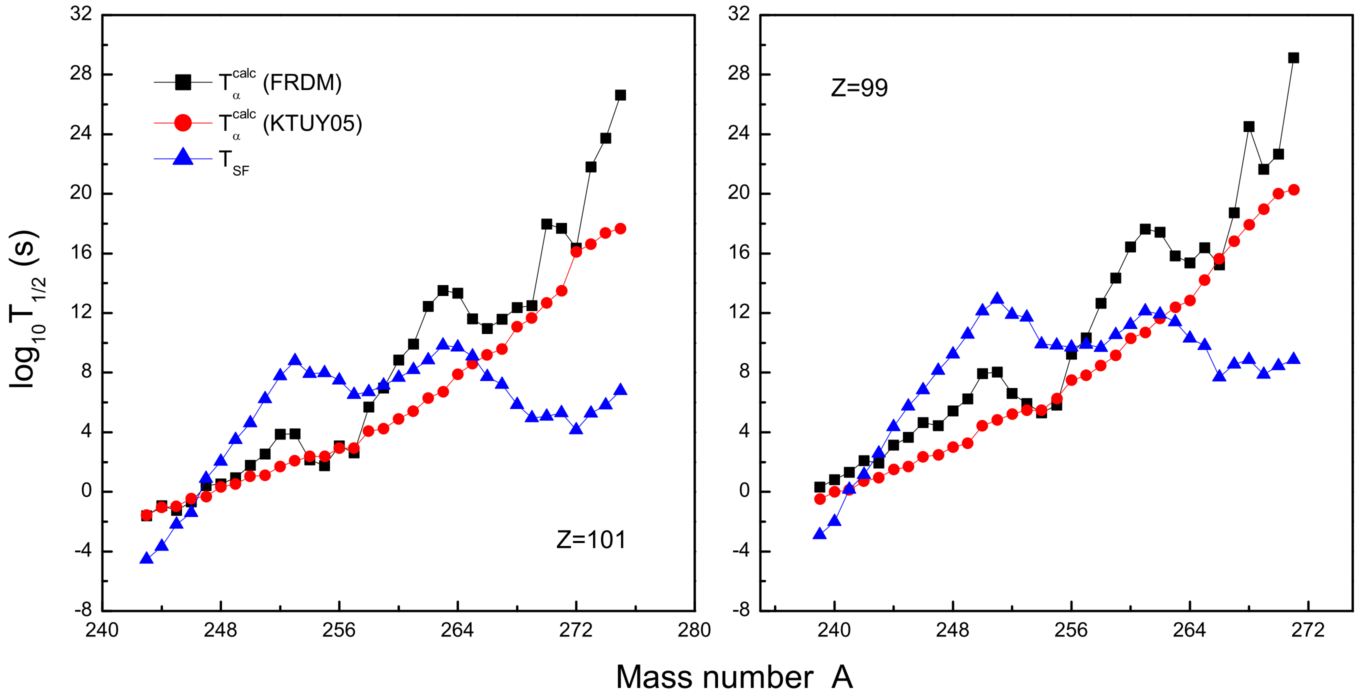

FIG. 4. (Color online) Same as Fig. 3 but for Md and Es isotopes.

TABLE III. Calculated results about the α decay and spontaneous fission half-lives of $^{299-290}$119. For each nucleus, the results of the first row are on the basis of FRDM masses [51], and those of the second row are from KTUY05 masses [52].

Nucleus	Q_α(MeV)	$T_\alpha^{\rm calc}$ (s)	$T_\alpha^{\rm VS}$ (s)	$T_\alpha^{\rm UD}$ (s)	$T_{\rm SF}$ (s)	Decay mode
^{299}119	12.86 [51]	1.40×10^{-5}	3.91×10^{-5}	3.72×10^{-5}	2.47×10^{3}	α
	11.54 [52]	1.14×10^{-2}	2.99×10^{-2}	3.22×10^{-2}	2.47×10^{3}	α
^{298}119	12.57 [51]	8.71×10^{-5}	5.47×10^{-4}	3.30×10^{-4}	1.96×10^{3}	α
	11.39 [52]	4.30×10^{-2}	2.43×10^{-1}	1.64×10^{-1}	1.96×10^{3}	α
^{297}119	12.81 [51]	1.82×10^{-5}	4.93×10^{-5}	4.71×10^{-5}	6.11×10^{2}	α
	11.35 [52]	3.49×10^{-2}	8.54×10^{-2}	9.39×10^{-2}	6.11×10^{2}	α
^{296}119	13.14 [51]	6.72×10^{-6}	3.87×10^{-5}	2.22×10^{-5}	2.98×10^{1}	α
	11.57 [52]	1.67×10^{-2}	9.03×10^{-2}	5.99×10^{-2}	2.98×10^{1}	α
^{295}119	12.95 [51]	1.03×10^{-5}	2.58×10^{-5}	2.44×10^{-5}	1.13×10^{2}	α
	11.77 [52]	3.68×10^{-3}	8.66×10^{-3}	9.14×10^{-3}	1.13×10^{2}	α
^{294}119	12.87 [51]	2.42×10^{-5}	1.33×10^{-4}	7.80×10^{-5}	4.38×10^{1}	α
	11.91 [52]	2.87×10^{-3}	1.48×10^{-2}	9.50×10^{-3}	4.38×10^{1}	α
^{293}119	12.95 [51]	1.09×10^{-5}	2.57×10^{-5}	2.44×10^{-5}	1.86×10^{1}	α
	12.05 [52]	9.01×10^{-4}	2.01×10^{-3}	2.07×10^{-3}	1.86×10^{1}	α
^{292}119	13.23 [51]	5.07×10^{-6}	2.58×10^{-5}	1.48×10^{-5}	8.21×10^{-1}	α
	12.16 [52]	8.41×10^{-4}	4.10×10^{-3}	2.57×10^{-3}	8.21×10^{-1}	α
^{291}119	13.27 [51]	2.76×10^{-6}	6.07×10^{-6}	5.60×10^{-6}	3.72×10^{-1}	α
	12.23 [52]	3.83×10^{-4}	8.09×10^{-4}	8.19×10^{-4}	3.72×10^{-1}	α
^{290}119	13.43 [51]	2.25×10^{-6}	1.07×10^{-5}	6.02×10^{-6}	1.94×10^{-2}	α
	12.37 [52]	3.13×10^{-4}	1.44×10^{-3}	8.87×10^{-4}	1.94×10^{-2}	α

FRDM or KTUY05 masses, which also check the validity of the present study. We just give the calculated α-decay half-lives in the present framework not including the results of UD and VS relationships in the following figures, for the sake of convenience and clear illustration. Figures 2–4 represent the $\log_{10} T_{1/2}$ against the mass number of nuclei for the isotopic chains of odd-Z elements 117–99. Interestingly, several features of decay properties for these heaviest isotopes are clearly shown in these figures: (i) with the decrease of Z number, the α-decay half-lives are close to the SF ones; (ii) the spontaneous fission tends towards the dominant decay mode along with two sides of one isotopic chain, especially for nuclei with large enough N number. In detail, the main mode of decay is generally the α transition for nuclei with $Z = 117$ and 115, and the situation of other isotopes is a little different. The SF half-life of isotopes with $Z \leqslant 113$ have been gradually comparable with that of α decay, leading that the α decay and SF processes have become competitive with each other. Hence the α-decay chains from elements 121 and 119 might be followed by the spontaneous fission of the mentioned isotopes with $Z \leqslant 113$ such as nuclei beyond ^{281}Rg, which is coherent with recent experiments [13–15]. There seems to be a clear trend that those heavier isotopes (about $N - Z \geqslant 62$) would not survive fission beginning from the element Rg, which is expected to strictly limit the existence of long-lived SHN. Sequently, on the other hand, on the basis of the new discovery of the long-lived α emitter ^{270}Db along with the predicted half-lives restricted by both the α decay and spontaneous fission (as shown in Figs. 1–4), we may conclude that the location of the "island of stability" is to the southwest in the nuclide chart with respect to ^{298}114. We hope that the present investigations and discussions can be useful for future experiments to search for new superheavy elements or nuclides.

IV. SUMMARY

To conclude, we study the α-decay half-lives of superheavy odd-Z nuclei, within the density-dependent cluster model including the nuclear deformation effect. The decay energy Q is obtained as the difference of the parent and the two decay products plus the electron screen correction, based on two calculated masses, namely the FRDM and KTUY05. The competition between α decay and spontaneous fission was then performed via an improved phenomenological description of spontaneous fission half-lives. In addition, the heavier cluster decay is supposed to be not competitive with the two decay modes from the empirical estimations. It is found that the calculated results are in good agreement with the available experimental data. In pace with the detailed analysis of our results, we attempt to present valuable information on decay properties of heaviest odd-Z nuclei. The detailed predictions on half-lives, e.g., for the attractive isotopes of 119, are meanwhile made, which can be helpful for experimentalists to detect and identify superheavy nuclei in future.

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[1] F. P. Heßberger, ChemPhysChem **14**, 483 (2013).
[2] C. F. von Weizsäcker, Z. Phys. **96**, 431 (1935).
[3] G. N. Flerov and G. M. Ter-Akopian, Rep. Prog. Phys. **46**, 817 (1983).
[4] W. Stephens, J. Klein, and R. Zurmühle, Phys. Rev. C **21**, 1664 (1980).
[5] F. Dellinger, O. Forstner, R. Golser, A. Priller, P. Steier, A. Wallner, G. Winkler, and W. Kutschera, Phys. Rev. C **83**, 065806 (2011).
[6] S. Hofmann and G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
[7] K. Morita *et al.*, J. Phys. Soc. Jpn. **73**, 2593 (2004).
[8] Yu Oganessian, J. Phys. G: Nucl. Phys. Part **34**, R165 (2007).
[9] P. A. Ellison *et al.*, Phys. Rev. Lett. **105**, 182701 (2010).
[10] L. Stavsetra, K. E. Gregorich, J. Dvorak, P. A. Ellison, I. Dragojević, M. A. Garcia, and H. Nitsche, Phys. Rev. Lett. **103**, 132502 (2009).
[11] Yu. Ts. Oganessian *et al.*, Phys. Rev. C **74**, 044602 (2006).
[12] Yu. Ts. Oganessian *et al.*, Phys. Rev. Lett. **104**, 142502 (2010); Phys. Rev. C **83**, 054315 (2011).
[13] Yu. Ts. Oganessian *et al.*, Phys. Rev. Lett. **109**, 162501 (2012).
[14] Yu. Ts. Oganessian *et al.*, Phys. Rev. C **87**, 054621 (2013).
[15] J. Khuyagbaatar *et al.*, Phys. Rev. Lett. **112**, 172501 (2014).
[16] P. Armbruster and G. Münzenberg, Eur. Phys. J. H **37**, 237 (2012).
[17] S. Hofmann *et al.*, Eur. Phys. J. A **48**, 62 (2012).
[18] K. Morita *et al.*, J. Phys. Soc. Jpn. **81**, 103201 (2012).
[19] Valery Zagrebaev and Walter Greiner, Phys. Rev. C **78**, 034610 (2008).
[20] V. I. Zagrebaev, A. V. Karpov, and Walter Greiner, Phys. Rev. C **85**, 014608 (2012).
[21] Yu. Ts. Oganessian *et al.*, Phys. Rev. C **79**, 024603 (2009).
[22] P. R. Chowdhury, C. Samanta, and D. N. Basu, Phys. Rev. C **77**, 044603 (2008).
[23] R. G. Lovas, R. J. Liotta, A. Insolia, K. Varga, and D. S. Delion, Phys. Rep. **294**, 265 (1998).
[24] Yuichi Hatsukawa, Hiromichi Nakahara, and Darleane C. Hoffman, Phys. Rev. C **42**, 674 (1990).
[25] B. A. Brown, Phys. Rev. C **46**, 811 (1992).
[26] D. N. Poenaru, I. H. Plonski, and W. Greiner, Phys. Rev. C **74**, 014312 (2006).
[27] B. Buck, A. C. Merchant, and S. M. Perez, At. Data Nucl. Data Tables **54**, 53 (1993).
[28] S. A. Gurvitz, P. B. Semmes, W. Nazarewicz, and T. Vertse, Phys. Rev. A **69**, 042705 (2004).
[29] V. Yu. Denisov and H. Ikezoe, Phys. Rev. C **72**, 064613 (2005).
[30] P. Mohr, Phys. Rev. C **73**, 031301(R) (2006).
[31] N. G. Kelkar and H. M. Castañeda, Phys. Rev. C **76**, 064605 (2007).
[32] D. S. Delion and R. J. Liotta, Phys. Rev. C **87**, 041302(R) (2013).
[33] S. Peltonen, D. S. Delion, and J. Suhonen, Phys. Rev. C **78**, 034608 (2008).
[34] G. Royer, J. Phys. G: Nucl. Part. Phys. **26**, 1149 (2000).
[35] Chang Xu and Zhongzhou Ren, Phys. Rev. C **73**, 041301(R) (2006).
[36] Dongdong Ni and Zhongzhou Ren, Phys. Rev. C **80**, 051303(R) (2009); **81**, 064318 (2010).
[37] Yuejiao Ren and Zhongzhou Ren, Phys. Rev. C **85**, 044608 (2012).
[38] V. Yu. Denisov and A. A. Khudenko, At. Data Nucl. Data Tables **95**, 815 (2009).
[39] E. L. Medeiros, M. M. N. Rodrigues, S. B. Duarte, and O. A. P. Tavares, J. Phys. G: Nucl. Part. Phys. **32**, B23 (2006).
[40] K. P. Santhosh, B. Priyanka, Jayesh George Joseph, and Sabina Sahadevan, Phys. Rev. C **84**, 024609 (2011).
[41] D. N. Basu, J. Phys. G: Nucl. Part. Phys. **30**, B35 (2004).
[42] A. I. Budaca and I. Silisteanu, Phys. Rev. C **88**, 044618 (2013).
[43] Chang Xu, Zhongzhou Ren, and Yanqing Guo, Phys. Rev. C **78**, 044329 (2008).
[44] M. Ismail, A. Y. Ellithi, M. M. Botros, and A. Adel, Phys. Rev. C **81**, 024602 (2010).
[45] W. M. Seif, M. Shalaby, and M. F. Alrakshy, Phys. Rev. C **84**, 064608 (2011).
[46] Yibin Qian, Zhongzhou Ren, and Dongdong Ni, Phys. Rev. C **83**, 044317 (2011).
[47] Yibin Qian and Zhongzhou Ren, Eur. Phys. J. A **49**, 5 (2013).
[48] V. E. Viola Jr. and G. T. Seaborg, J. Inorg. Nucl. Chem. **28**, 741 (1966).
[49] D. Ni, Z. Ren, T. Dong, and C. Xu, Phys. Rev. C **78**, 044310 (2008).
[50] D. N. Poenaru, R. A. Gherghescu, and W. Greiner, Phys. Rev. Lett. **107**, 062503 (2011); Phys. Rev. C **85**, 034615 (2012).
[51] P. Möller, J. R. Nix, W. D. Myers, and W. J. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).
[52] H. Koura, T. Tachibana, M. Uno, and M. Yamada, Prog. Theor. Phys. **113**, 305 (2005).
[53] G. R. Satchler and W. G. Love, Phys. Rep. **55**, 183 (1979).
[54] A. M. Kobos, B. A. Brown, P. E. Hodgson, G. R. Satchler, and A. Budzanowski, Nucl. Phys. A **384**, 65 (1982).
[55] K. Wildermuth and Y. C. Tang, *A Unified Theory of the Nucleus* (Academic Press, New York, 1997).
[56] P. E. Hodgson and E. Běták, Phys. Rep. **374**, 1 (2003).
[57] Yibin Qian and Zhongzhou Ren, Sci. China-Phys. Mech. Astron. **56**, 1520 (2013).
[58] A. V. Karpov, V. I. Zagrebaev, Y. Martinez Palenzuela, L. Felipe Ruiz, and Walter Greiner, Int. J. Mod. Phys. E **21**, 1250013 (2012).
[59] Zhongzhou Ren and Chang Xu, Nucl. Phys. A **759**, 64 (2005).
[60] V. I. Zagrebaev *et al.*, http://nrv.jinr.ru/nrv/.