Predictions for decay modes for superheavy nuclei $Z = 118–124$

Tian Liang Zhao (赵天亮) and Xiao Jun Bao (包小军)*
Department of Physics, Collaborative Innovation Center for Quantum Effects, and Key Laboratory of Low Dimensional Quantum Structures and Quantum Control of Ministry of Education, Hunan Normal University, Changsha 410081, People's Republic of China

(Received 23 July 2018; published 6 December 2018)

To study whether long-lived superheavy nuclei could really exist around $Z = 120$ and $N = 184$, the competition between α decay and spontaneous fission in the region $104 \leqslant Z \leqslant 124$ are systemically studied. The α-decay half-lives are investigated by employing a generalized liquid drop model and the analytical universal decay law formula. The calculation of spontaneous fission half-lives are carried out based on generalized Swiatecki's formula. The competition between α decay and spontaneous fission is analyzed in detail and the decay modes are predicted for the unknown nuclei.

DOI: 10.1103/PhysRevC.98.064307

I. INTRODUCTION

The synthesis of superheavy nuclei (SHN) has always been an important topic in nuclear physics [1–6], the stability and decay properties of the SHN have been a longstanding fundamental question [7–13]. It is well known that α decay and spontaneous fission are the main modes of decay for SHN [14–18]. Experimentally, the unambiguous identification of the new isotopes still poses a problem because their α-decay chains terminate by spontaneous fission before reaching the known region of the nuclear chart [19–28]. Theoretical understanding of the competition between α decay and spontaneous fission is of crucial importance.

In recent years, many theoretical models have been developed to calculate the α decay half-lives of SHN [29–43]. The simple empirical relations between α-decay half-lives and decay energies have also been discussed [44–53]. The calculated α-decay half-lives are in agreement with the experimental data. The α-decay half-lives of SHN are predicted within different theoretical models or empirical formulas using Q_α values from different mass formulas.

Compared with α decay, spontaneous fission is a much more complex process and not satisfactorily understood yet [54–64]. However, it plays an important role because the α-decay chains of SHN tend to end with spontaneous fission such as ^{293,294}Mc [5]. If we can obtain the shape and width of the fission barrier, the computation of the spontaneous fission half-lives is reduced to solve the possibility of barrier penetration [10,14]. Many methods have been developed to describe the fission barriers and spontaneous fission half-lives [65–75]. Very recently, theoretical uncertainties in the predictions of inner fission barrier heights in SHN have been investigated in a systematic way based on covariant energy density functionals, with the difference in the inner fission barrier height of some SHN reaching 5–6 MeV [76]. This uncertainty in the fission barrier heights will be translated into huge uncertainties in the spontaneous fission half-lives.

Compared with the theoretical results of competition between α decay and spontaneous fission for even-even SHN, those of odd-Z nuclei seem to be rare [77–81]. In the present work, three modified formulas including the microscopic shell correction [72–74] are used to determine the spontaneous fission half-lives based on the Swiatecki formula. The α-decay half-lives of the SHN are studied based on the frameworks of the generalized liquid drop model (GLDM) [82–85] and the analytical universal decay law (UDL) formula [48,49]. The stability of superheavy nuclei against these two important decay modes and the competition between them are discussed. This work aims at the interpretation of existing experimental decay modes and predictions of decay modes of yet unknown nuclei.

II. THEORETICAL FRAMEWORK

A. α-decay half-lives

Very recently, in order to test the abilities of our calculations on the α-decay half-lives by using analytic formula and semiclassical approaches, the α-decay half-lives of SHN with $Z \geqslant 104$ have been systematically studied. The results of systematic calculation demonstrate that the UDL formula and the GLDM with consideration of the preformation factor give fairly equivalent results for the SHN [86].

The UDL formula is written as

$$\log_{10} T_{1/2}(s) = aZ_\alpha Z_d\sqrt{\frac{A_dA_\alpha}{(A_d+A_\alpha)Q_\alpha}} + b\sqrt{\frac{A_dA_\alpha}{(A_d+A_\alpha)}Z_\alpha Z_d\left(A_d^{1/3}+A_\alpha^{1/3}\right)} + c. \tag{1}$$

Here Q_α is the decay energy in MeV units, and Z_d and A_d are the charge and mass number of the daughter nuclei,

*baoxiaojun@hunnu.edu.cn

respectively. The UDL formula has been derived from the microscopic description of the α decay [48] or the first principles of quantum mechanics [49]. The parameters a, b, and c are addressed in detail in Ref. [86].

In the GLDM, the α-decay constant is defined as,

$$\lambda = P_\alpha \nu_0 P. \quad (2)$$

The assault frequency ν_0 is calculated phenomenologically as addressed in detail in Ref. [87],

$$\nu_0 = \frac{1}{2R}\sqrt{\frac{2E_\alpha}{M}}. \quad (3)$$

The barrier penetrability P is computed within the action integral

$$P = \exp\left\{-\frac{2}{\hbar}\int_{R_{\rm in}}^{R_{\rm out}} \sqrt{2\mu[V_2(r) - Q_\alpha]}dr\right\}, \quad (4)$$

where $R_{\rm in}$ and $R_{\rm out}$ are the two turning points of the WKB action integral. The two following approximations have been used here:

$$R_{\rm in} = R_1 + R_2, R_{\rm out} = e^2 Z_1 Z_2/Q_\alpha, \quad (5)$$

where R_1, R_2 are the radius of α cluster and daughter nucleus, respectively. The $V_2(r)$ has been researched in Ref. [88], where the potential $V_2(r)$ has been determined within a liquid drop model [82,83]. In the present work, the preformation factor is adopted by an analytic formula [87]:

$$P_\alpha = \exp[a + b(Z - Z_1)(Z_2 - Z) + c(N - N_1)(N_2 - N) + dA], \quad (6)$$

where Z, N, and A are the charge, neutron, and mass number of the parent nucleus, respectively, which provided general guidance for the microscopic study on the α-particle preformation factor. The preformation factor P_α is addressed in detail in Ref. [87]. Finally, the decay constant is simply defined as $\lambda = P_\alpha \nu_0 P$ and half-lives can be obtained by $T = \ln 2/\lambda$.

B. Spontaneous fission half-lives

The spontaneous fission half-life is inversely proportional to the probability P of the penetrability through the barrier based on the WKB approximation. The spontaneous fission half-life T_{SF} is calculated by the formula

$$T_{SF} = \frac{\ln 2}{\nu_0 P}, \quad (7)$$

where ν_0 denotes the number of assaults of the nucleus on the fission barrier in a time unit. We assume fission barriers by using the parabolic potential approximation, the penetrability probability P for such a barrier will be [89]

$$P = [1 + \exp 2\pi(V_f - E)/\hbar\omega_f]^{-1}. \quad (8)$$

The fission barrier is determined from potential energy surfaces calculated according to the macroscopic-microscopic method [91]. In order to determine the fission barrier, the nuclear binding energy is expressed as

$$E = E_{LD} + E_{\rm shell}. \quad (9)$$

The barrier height V_f can be given by the potential energy surfaces difference [54,90],

$$V_f = \Delta E_{LD} + \Delta E_{\rm shell}. \quad (10)$$

The difference ΔE_{LD} between the smooth liquid drop potential energy surface should be a regular function of the fissility parameter $Z^2/(1 - kI^2)A$,

$$\Delta E_{LD} = f(Z^2/(1 - kI^2)A. \quad (11)$$

In the present work, we make the assumption that shell effects have disappeared by the saddle point. It is seen from Ref. [92] that shell effects indeed practically vanish at the saddle configuration. Finally, the fission barrier can be expressed:

$$E_f = f(Z^2/(1 - kI^2)A) + E_{\rm shell}, \quad (12)$$

where $E_{\rm shell}$ is the microscopic correction energy.

Thus, incorporating Eqs. (8)–(12) into Eq. (7) we may express the spontaneous fission half-lives,

$$\log_{10} T_{1/2}(yr) = c_1 + c_2\left(\frac{Z^2}{(1 - kI^2)A}\right) + c_3\left(\frac{Z^2}{(1 - kI^2)A}\right)^2 + c_4 E_{\rm shell} + h_i. \quad (13)$$

$E_{\rm shell}$ is the microcosmic energy taken from FRDM [91]. This semiempirical formula is similar to the Swiateck's formula [55], which is addressed in detail in Ref [73].

The second is the Santhosh (KPS) formula [74], which is written as

$$\log_{10} T_{1/2}(yr) = a\frac{Z^2}{A} + b\left(\frac{Z^2}{A}\right)^2 + c\left(\frac{N - Z}{N + Z}\right) + d\left(\frac{N - Z}{N + Z}\right)^2 + eE_{\rm shell} + f, \quad (14)$$

where the parameters are $a = -43.25203$, $b = 0.49192$, $c = 3674.3927$, $d = -9360.6$, $e = 0.8930$, and $f = 578.56058$. $E_{\rm shell}$ is the microscopic energy taken from Ref. [93].

The third formula to calculate spontaneous fission half-life is the Karpov (AVK) formula [72], which reads

$$\log_{10} T_{1/2}(s) = 1146.44 - 75.3153Z^2/A + 1.63792(Z^2/A)^2 - 0.0119827(Z^2/A)^3 + B_f(7.23613 - 0.0947022Z^2/A) + h. \quad (15)$$

In Ref. [72], B_f is the fission barrier, which is calculated as a sum of the liquid drop barrier $B_f(LDM)$ and the ground-state shell correction $\delta U(g.s.)$, i.e., $B_f = B_f(LDM) + \delta U(g.s.)$. The $h = 0$ for the nuclei when Z and N are even. When A is odd, $h = 1.53897$, and when both Z and N are odd, $h = 0.80822$. However, we find that the AVK formula replaced the microscopic shell correction $E_{\rm shell}$ by the fission barrier B_f. According to the expression of tunneling probability P as

TABLE I. Experiment half-lives for SHN compared with calculated half-lives by the UDL formula and GLDM to α decay and three formulas to spontaneous fission [97].

Nuclei	$\log_{10}(T^{\alpha}_{1/2})$ (Exp.)	$\log_{10}(T^{\alpha}_{1/2})$ (UDL)			$\log_{10}(T^{\alpha}_{1/2})$ (GLDM)			$\log_{10}(T^{SF}_{1/2})$ (Exp.)	$\log_{10}(T^{SF}_{1/2})$ (Cal.)		
		Q_α (Exp.)	Q_α (WS)	Q_α (FRDM)	Q_α (Exp.)	Q_α (WS)	Q_α (FRDM)		Bao	KPS	NAVK
^{294}Og	−3.161	−3.667	−4.398	−4.697	−3.109	−3.802	−4.091		4.666	8.333	19.480
^{293}Ts	−1.658	−2.318	−3.033	−3.172	−1.810	−2.498	−2.634		8.279	6.910	12.638
^{294}Ts	−1.292	−1.533	−1.872	−2.735	−2.044	−2.376	−3.217		11.649	6.458	6.586
^{290}Lv	−2.081	−2.246	−2.530	−2.537	−1.801	−2.079	−2.085		3.711	5.642	17.863
^{291}Lv	−1.721	−1.527	−2.031	−2.100	−1.064	−1.555	−1.623		7.186	5.296	11.945
^{292}Lv	−1.886	−1.710	−2.480	−1.828	−1.337	−2.090	−1.456		5.343	4.739	18.951
^{293}Lv	−1.244	−1.089	−1.352	−1.676	−0.702	−0.969	−1.282		9.026	4.173	13.190
^{287}Mc	−1.432	−1.455	−1.224	−0.060	−0.915	−0.685	0.483		5.749	4.978	9.754
^{288}Mc	−0.759	−0.676	−0.329	0.717	−1.109	−0.764	0.292		9.700	4.802	4.296
^{289}Mc	−0.481	−0.770	−0.340	0.535	−0.325	0.107	0.991		7.117	4.110	10.580
^{290}Mc	−0.187	−0.115	−0.030	1.293	−0.482	−0.394	0.944		10.904	3.680	4.903
^{285}Fl	−0.824	1.847	−1.496	2.312	2.373	−0.981	2.839		4.321	3.583	8.761
^{286}Fl	−0.699	−1.134	−0.847	1.682	−0.771	−0.482	2.057		1.539	3.052	14.951
^{287}Fl	−0.319	−0.197	0.162	2.406	0.250	0.611	2.863		5.429	2.780	9.403
^{288}Fl	−0.180	−0.383	0.513	2.392	−0.087	0.814	2.702		3.021	2.161	15.927
^{289}Fl	0.279	0.312	0.946	3.841	0.672	1.309	4.220		7.555	1.672	10.854
^{282}Nh	−1.137	−1.636	−2.246	1.129	−1.978	−2.580	0.797		3.958	2.466	−1.548
^{283}Nh	−1.125	−1.054	−1.804	1.944	−0.562	−1.313	2.443		1.586	2.136	5.099
^{284}Nh	−0.013	0.100	−0.710	3.056	−0.188	−1.001	2.775		5.515	2.025	−0.393
^{285}Nh	0.623	−0.059	−0.387	3.150	0.363	0.035	3.581		3.143	1.402	6.237
^{286}Nh	0.978	1.017	0.942	3.824	0.808	0.732	3.623		6.969	1.039	0.596
^{281}Cn	−0.886	−1.576	−1.843	−0.694	−1.087	−1.357	−0.203		−1.618	0.680	3.123
^{282}Cn		0.747	−1.511	0.951	1.047	−1.232	1.253	−3.041	−3.783	0.289	10.034
^{283}Cn	0.655	0.641	−0.197	2.670	1.039	0.201	3.071		0.317	0.072	4.666
^{284}Cn		2.213	−0.179	3.289	2.424	0.028	3.505	−1.009	−2.155	−0.646	11.317
^{285}Cn	0.447	1.651	1.171	4.079	1.977	1.497	4.415		1.807	−1.121	5.773
^{278}Rg	−2.377	−2.408	−3.122	−3.691	−2.603	−3.301	−3.851		0.456	0.600	−4.775
^{279}Rg	−1.046	−2.065	−2.608	−3.064	−1.581	−2.129	−2.568		−2.954	−0.110	1.264
^{280}Rg	0.623	0.059	−1.218	−0.571	−0.072	−1.357	−0.708		0.778	−0.292	−4.358
^{281}Rg		1.070	−0.754	1.209	1.480	−0.357	1.620	1.286	−1.894	−0.935	2.233
^{282}Rg	2.000	2.292	0.871	3.532	2.247	0.817	3.496		2.240	−1.322	−3.181
^{277}Ds	−2.387	−2.851	−2.950	−2.788	−2.393	−2.494	−2.329		−2.127	−0.244	2.721
^{279}Ds		−0.560	−1.673	−0.084	−0.168	−1.289	0.311	−0.627	−3.125	−1.631	2.431
^{281}Ds		2.492	0.755	3.539	2.813	1.067	3.867	1.135	−2.142	−2.939	3.374
^{274}Mt	−0.357	−1.337	−1.562	−0.945	−1.408	−1.635	−1.015		5.089	1.099	−1.984
^{275}Mt	−1.699	−2.543	−2.112	−1.443	−2.107	−1.679	−1.004		0.534	0.071	3.496
^{276}Mt	−0.347	−0.910	−0.826	−0.620	−0.907	−0.822	−0.615		2.072	−0.719	−3.485
^{277}Mt		−0.761	−0.574	−0.866	−0.394	−0.207	−0.500	−2.301	−2.727	−1.956	2.050
^{278}Mt	0.653	0.335	0.105	0.948	0.418	0.187	1.032		−0.083	−2.627	−4.226
^{273}Hs	−0.119	−0.827	−0.193	0.063	−0.410	0.224	0.479		1.944	0.367	5.046
^{275}Hs	−0.699	−0.046	0.689	0.118	0.296	1.032	0.460		−1.522	−1.715	3.768
^{277}Hs		1.933	1.429	2.143	2.207	1.701	2.417	−2.523	−3.488	−3.935	3.461
^{270}Bh	1.785	1.315	2.383	4.277	1.420	2.493	4.400		7.950	1.732	−0.937
^{271}Bh	0.176	−0.253	0.862	2.160	0.183	1.304	2.608		3.868	0.892	5.061
^{272}Bh	1.025	0.908	1.350	1.838	1.085	1.529	2.021		5.370	0.028	−1.761

TABLE I. (*Continued.*)

Nuclei	$\log_{10}(T^{\alpha}_{1/2})$ (Exp.)	$\log_{10}(T^{\alpha}_{1/2})$ (UDL)			$\log_{10}(T^{\alpha}_{1/2})$ (GLDM)			$\log_{10}(T^{SF}_{1/2})$ (Exp.)	$\log_{10}(T^{SF}_{1/2})$ (Cal.)		
		Q_α (Exp.)	Q_α (WS)	Q_α (FRDM)	Q_α (Exp.)	Q_α (WS)	Q_α (FRDM)		Bao	KPS	NAVK
^{274}Bh	1.643	1.628	2.399	2.395	1.833	2.606	2.602		2.293	−2.314	−2.495
^{269}Sg	2.270	1.658	3.392	5.177	2.075	3.819	5.619		4.472	1.224	6.166
^{271}Sg		1.723	2.198	2.624	2.070	2.547	2.976	2.219	1.806	−0.797	5.716
^{266}Db		6.183	4.334	6.764	6.438	4.573	7.025	3.121	7.207	2.094	−1.207
^{267}Db		6.420	5.095	7.462	6.844	5.505	7.900	3.670	5.216	1.682	5.732
^{268}Db		6.688	4.460	7.458	7.026	4.776	7.805	5.008	7.962	1.134	−0.527
^{270}Db		4.279	3.568	4.732	4.673	3.957	5.130	4.732	5.170	−1.237	−0.687
^{265}Rf		6.920	4.489	7.453	7.323	4.867	7.862	1.778	4.064	1.861	6.672
^{267}Rf		7.419	4.620	8.151	7.756	4.926	8.498	3.670	4.589	0.547	7.377

derived from Eqs. (8)–(12), this leads to double counting of the macroscopic energy.

III. NUMERICAL RESULTS AND DISCUSSIONS

A. α-decay half-lives

Systematic calculations on the α-decay half-lives of SHN are performed with the GLDM and the analytical formula of UDL by the experimental Q_α values. We found that the UDL formula is very appropriate to describe the α-decay half-lives of SHN [86]. Because the results from the GLDM are in fair agreement with the experimental data, which indicates that GLDM is a useful tool to investigate the half-lives of α decay when the experimental Q_α values are given [86]. It is well known that the α-decay half-life is sensitive to changes in Q_α; a change in the Q_α value by 1 MeV may result in a change of half-life of about three orders of magnitude or even more. Up to now, however, there has been almost no approach that could provide an accurate Q_α value theoretically with a deviation of less than 0.3 MeV.

In order to compare the predictive power of α decay Q_α from different mass models, we have performed the calculations on the α decay Q_α of the 74 SHN with $Z \geqslant 104$ by the microscopic-macroscopic model based on the deformed Woods-Saxon potential (MMM) [94], the finite-range droplet model (FRDM) [91], the Koura-Tachibana-Uno-Yamada (KTUY) [95], and Weizsäcker-Skyrme (WS) [96]. To show the global deviation between the experimental and calculated Q_α values, the root mean square (RMS) deviations are calculated. By comparing the calculated results, we can find that the RMS of MMM is 0.360, WS is 0.263, FRDM is 0.547, and KTUY is 0.421. From these values, we can consider WS as a better method for Q_α than MMM, FRDM, and KTUY to describe decay energy. However, to study the influence of the α decay Q_α on the half-lives and decay mode, we take two different models for calculation of the Q_α (WS and FRDM).

B. Spontaneous fission of half-lives

As is pointed out in Sec. I, calculations of the spontaneous fission half-lives of SHN are extremely sensitive to the height of the fission barrier. Through theoretical discussion on the calculation of the spontaneous fission half-lives in Sec. II B, we replace the fission barrier height B_f in the AVK formula with shell correction E_{shell}. In the present work, we choose 45 even-even nuclei, 12 odd-Z nuclei, and 12 odd-N nuclei whose spontaneous fission half-lives are known from Ref. [73]. We refit the parameters in the AVK formula

$$\log_{10} T_{1/2}(yr) = c_1 + c_2\frac{Z^2}{A} + c_3\left(\frac{Z^2}{A}\right)^2 + c_4\left(\frac{Z^2}{A}\right)^3 + E_{\text{shell}}\left(c_5 - c_6\frac{Z^2}{A}\right) + h, \tag{16}$$

where E_{shell} is the shell correction energy taken from Ref. [91].

First, for even-even (Z-N) nuclei, the parameter h is 0. So we can fit other parameters to the spontaneous fission half-lives. The parameters $c_1 = -764.211$, $c_2 = 68.648$, $c_3 = -1.875$, $c_4 = 0.016$, $c_5 = -19.786$, $c_6 = -0.503$. Then, we fit the spontaneous fission half-lives for 12 odd-N and 12 odd-Z nuclei. We get the parameter $h_{eo} = -6.524$ and $h_{oe} = -7.361$ to fix the new AVK (NAVK) formula with the values c_1-c_6, and $h_{oo} = h_{eo} + h_{oe}$. We calculate the spontaneous fission half-lives by using refit AVK formula, and the RMS from the experimental spontaneous fission half-life of 45 even-even nuclei is found to be 2.08. The value is larger than the RMS of the KPS formula 1.70 [74] and Bao formula 1.10 [73]. Compared to AVK formula without isospin effect, one can find that the isospin effect contributions are considered in the analytical formula (Bao and KPS formula), the theoretical results can better reproduce the experimental spontaneous fission half-lives.

C. Prediction the mode of decay for $Z = 118$–124

According to the above calculations, we now discuss the competition between α decay and spontaneous fission. We calculate the α-decay and the spontaneous fission half-lives and the results are shown in Table I, and compared with available experimental results [97]. We find that the analytical formula of UDL is also very appropriate to describe the α-decay half-lives. The calculated α half-lives from the GLDM are in good agreement with the experimental data, which indicates that the GLDM and UDL are useful tools to investigate the half-lives for α decay when the reliable Q_α values are determined by theoretical models. The experimental and theoretical spontaneous fission half-lives are also compared in the last four columns of Table I. The agreement between the calculated results and the experimental data is roughly good.

By comparing the half-lives for α decay with those for spontaneous fission, one can identify the decay mode of each nucleus. We show that the decay modes are determined by different methods and compared with the experimental data from ^{267}Rf to ^{294}Og. The α-decay half-lives of SHN have been calculated with the GLDM and the analytical UDL formula using the experimental Q_α values. The modified Swiatecki formulas (Bao formula, KPS formula and AVK formula) are used to evaluate the half-lives for spontaneous fission. The theoretical calculation of the competition mode is judged by one order of magnitude between α decay and spontaneous fission ($0.1 \leqslant T_\alpha/T_{SF} \leqslant 10$). By using the experimental Q_α value to calculate the half-life for α decay, then compared the second column with the third column in Table II, one can see that the calculated decay modes are in agreement with the experimental data [97].

In Table II, the α-decay half-lives are also calculated by using the Q_α values taken from the mass table WS. The modified Swiatecki formula (Bao formula) is used to evaluate the half-lives for spontaneous fission. The fourth column gives the decay mode determined by the α-decay half-lives of the mass table WS. As one may notice, our calculations agree well with the experimental decay modes. In addition, we adopt the generalized Swiatecki's formula (Bao formula) for calculating the half-lives for the spontaneous fission by using the shell correction taken from FRDM, and Q_α values of the SHN are also obtained within the mass table of FRDM for calculating the half-lives for the α decay. The fifth column gives the α half-life determined by FRDM Q_α value, then the decay mode is determined. The calculated decay modes are in good agreement with the experimental data.

In order to study the effect of the uncertainty of spontaneous fission half-life on the decay mode, we compare the decay modes determined by three different spontaneous fission half-lives based on the same α-decay half-lives. It can be seen from the results of Table II that the KPS formula accurately reproduced 34/35/28 experimental values, the Bao formula was 38/36/36, and the NAVK formula was 31/30/30 if we calculated the half-life of α decay based on the experimental, WS and FRDM Q_α value, respectively. This fact suggests that for a given SHN, the decay mode is determined mainly by spontaneous fission half-lives. From Table II, we also find that decay mode is sensitive to the Q_α value, even though it is less obvious than that of spontaneous fission. It is anticipated that the majority of SHN would α decay and/or fission, but predictions vary from model to model, primarily due to our inability to make accurate predictions for spontaneous fission half-lives. By comparing the decay modes determined by different methods, we find that the methods considered the isospin effect greatly improve the ability of theory to reproduce experimental decay modes.

Although both the Bao formula and the KPS formula contain the influence of the shell corrections and isospin effect on the spontaneous fission half-lives, we see from Figs. 1–4 that there are still significant differences in the spontaneous fission half-lives of the two formulas. By comparing the results of the KPS formula and Bao formula, we find that the trend is roughly the same for $N < 184$, but the difference of spontaneous fission half-lives is about several orders of magnitude. For $N \geqslant 184$, there are significant differences between the two formulas, or even the opposite trend. And we find that in the calculation of the KPS formula, the half-life of spontaneous fission is almost reduced as the decay progresses. However, experiments and theories show that the shell correction provides additional stability for the SHN [25,97]. The effect of the nuclear structure on the decay chain almost disappeared based on the KPS formula. Therefore, it is very important to consider isospin effect and shell effect reasonably in formulas for calculating the half-lives of spontaneous fission.

Through the above description and discussion, we used the UDL formula and GLDM to calculate α-decay half-lives with Q_α from WS and FRDM, and compared with Bao formula to calculate spontaneous fission half-lives. In the present work, we calculated nucleus decay chain and predict the mode of decay $Z = 118$–124. We have selected 12 isotopes of SHN with $Z = 124$ and $Z = 123$, respectively, for studying the α-decay chains. Through Figs. 1–2, we can find some of the rules. α decay is a main decay mode when decay begins $N \leqslant 184$. After about six or five times of α decay, there are competition for spontaneous fission and α decay. Figures 3–4 represent the comparison between the α-decay and spontaneous fission half-lives for SHN ^{295,296,309,310}122, ^{294,295,308,309}121, ^{289,290,307,308}120, ^{288,289,306,307}119, and ^{283,284,305,306}118. The decays of these nuclei are not included in the α-decay chain of Figs. 1–2. By comparing the α-decay half-lives and spontaneous fission half-lives and then determined decay modes, we would like to point out our conclusion about perspectives of employing the fusion reactions for synthesis of new SHN with $Z = 118$–124 and $174 \leqslant N \leqslant 184$, the main decay mode of these nucleus is α decay. This conclusion is based on a rather simple phenomenological model that calculated the half-lives of spontaneous fission. In order to verify this finding, more fundamental calculations should be made to take into account the odd-nucleon blocking effects and the multidimensional potential energy surface of the fission process [57–60,62,63].

The present calculated half-lives agree with the experimental ones, the calculations are extended to provide some predictions for α-decay and spontaneous fission half-lives, which will be useful for future experiments to synthesize and

TABLE II. Theoretical decay modes are compared with experimental decay modes [97].

Nucleus	mode (exp)	mode (Bao)			mode (KPS)			mode(NAVK)		
		Q_α (Exp)	Q_α (WS)	Q_α (FRDM)	Q_α (Exp)	Q_α (WS)	Q_α (FRDM)	Q_α (Exp)	Q_α (WS)	Q_α (FRDM)
^{294}Og	α	α	α	α	α	α	α	α	α	α
^{293}Ts	α	α	α	α	α	α	α	α	α	α
^{294}Ts	α	α	α	α	α	α	α	α	α	α
^{290}Lv	α	α	α	α	α	α	α	α	α	α
^{291}Lv	α	α	α	α	α	α	α	α	α	α
^{292}Lv	α	α	α	α	α	α	α	α	α	α
^{293}Lv	α	α	α	α	α	α	α	α	α	α
^{287}Mc	α	α	α	α	α	α	α	α	α	α
^{288}Mc	α	α	α	α	α	α	α	α	α	α
^{289}Mc	α	α	α	α	α	α	α	α	α	α
^{290}Mc	α	α	α	α	α	α	α	α	α	α
^{285}Fl	α	α	α	α	α	α	α/SF	α	α	α
^{286}Fl	α:0.6	α	α	α/SF	α	α	α/SF	α	α	α
^{287}Fl	α	α	α	α	α	α	α/SF	α	α	α
^{288}Fl	α	α	α	α/SF	α	α	α/SF	α	α	α
^{289}Fl	α	α	α	α	α/SF	α/SF	SF	α	α	α
^{282}Nh	α	α	α	α	α	α	α	α/SF	α/SF	SF
^{283}Nh	α	α	α	α/SF	α	α	α/SF	α	α	α
^{284}Nh	α	α	α	α	α	α	α/SF	α/SF	α/SF	SF
^{285}Nh	α	α	α	α/SF	α	α	SF	α	α	α
^{286}Nh	α	α	α	α	α/SF	α/SF	SF	α/SF	α/SF	SF
^{281}Cn	α	α/SF	α/SF	α/SF	α	α	α/SF	α	α	α
^{282}Cn	SF	SF	SF	SF	α/SF	α	α/SF	α	α	α
^{283}Cn	$\alpha \geqslant 0.93$	α/SF	α/SF	SF	α/SF	α/SF	SF	α	α	α
^{284}Cn	SF	SF	SF	SF	SF	α/SF	SF	α	α	α
^{285}Cn	α	α/SF	α/SF	SF	SF	SF	SF	α	α	α
^{278}Rg	α	α	α	α	α	α	α	SF	SF	α/SF
^{279}Rg	α	α/SF	α/SF	α/SF	α	α	α	α	α	α
^{280}Rg	α	α/SF	α	α	α/SF	α/SF	α/SF	SF	SF	SF
^{281}Rg	SF:0.88	SF	SF	SF	SF	α/SF	SF	α/SF	α	α
^{282}Rg	α	α/SF	α	SF	SF	SF	SF	SF	SF	SF
^{277}Ds	α	α/SF	α/SF	α/SF	α	α	α	α	α	α
^{279}Ds	SF:0.89	SF	SF	SF	SF	α/SF	SF	α	α	α
^{281}Ds	SF:0.93	SF	SF	SF	SF	SF	SF	α/SF	α	α/SF
^{274}Mt	α	α	α	α	α	α	α	α/SF	α/SF	α/SF
^{275}Mt	α	α	α	α	α	α	α	α	α	α
^{276}Mt	α	α	α	α	α/SF	α/SF	α/SF	SF	SF	SF
^{277}Mt	SF	SF	SF	SF	SF	SF	SF	α	α	α
^{278}Mt	α	α/SF	α/SF	SF	SF	SF	SF	SF	SF	SF
^{273}Hs	α	α	α	α	α/SF	α/SF	α/SF	α	α	α
^{275}Hs	α	SF	SF	SF	SF	SF	SF	α	α	α
^{277}Hs	SF	SF	SF	SF	SF	SF	SF	α	α	α
^{270}Bh	α	α	α	α	α/SF	α/SF	SF	SF	SF	SF
^{271}Bh	α	α	α	α	α/SF	α/SF	SF	α	α	α
^{272}Bh	α	α	α	α	α/SF	SF	SF	SF	SF	SF
^{274}Bh	α	α/SF	α/SF	α/SF	SF	SF	SF	SF	SF	SF
^{269}Sg	α	α	α/SF	α/SF	α/SF	SF	SF	α	α	α/SF
^{271}Sg	SF:0.58	α/SF	α/SF	α/SF	SF	SF	SF	α	α	α
^{266}Db	SF	α/SF	α	α/SF	SF	SF	SF	SF	SF	SF
^{267}Db	SF	SF	α/SF	SF	SF	SF	SF	α/SF	α/SF	SF
^{268}Db	SF	α/SF	α	α/SF	SF	SF	SF	SF	SF	SF
^{270}Db	SF	α/SF	α	α/SF	SF	SF	SF	SF	SF	SF
^{265}Rf	SF	SF	α/SF	SF	SF	SF	SF	α/SF	α	α/SF
^{267}Rf	SF	SF	α/SF	SF	SF	SF	SF	α/SF	α	α/SF
		38/54	36/54	36/54	34/54	35/54	28/54	31/54	30/54	30/54

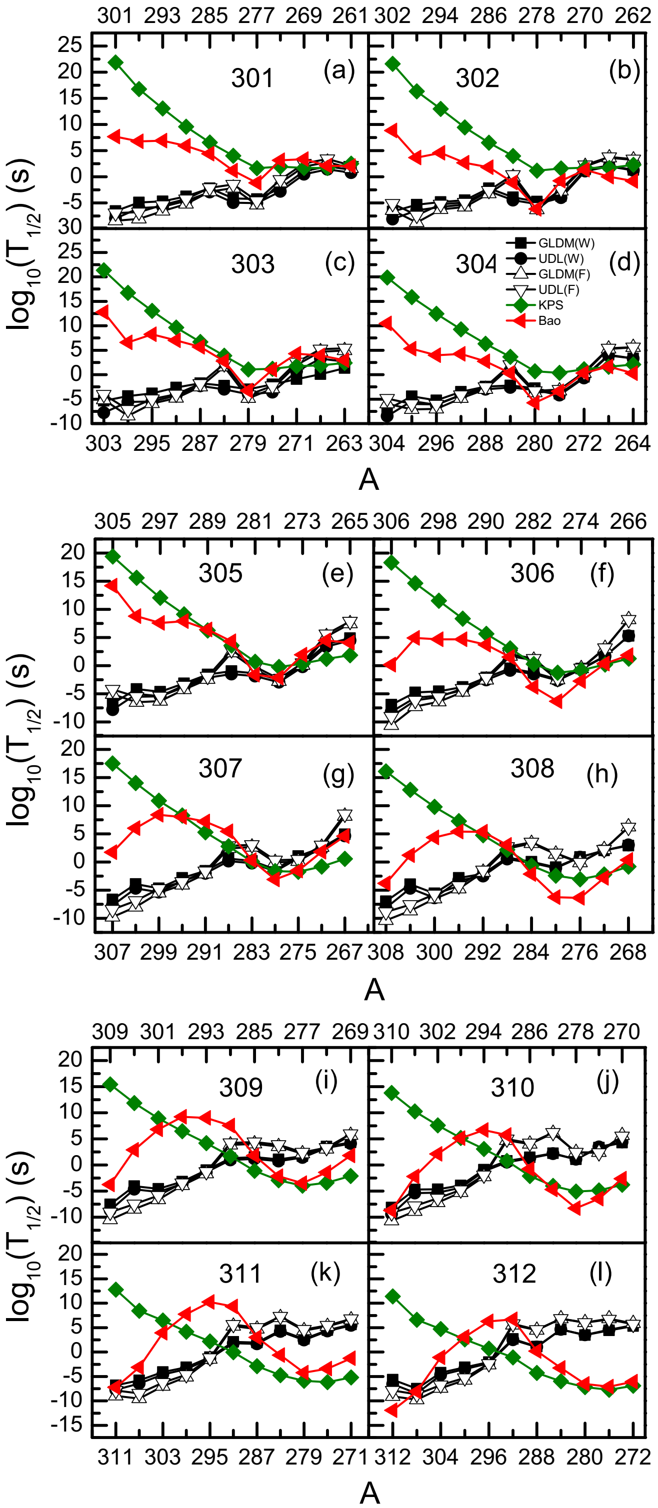

FIG. 1. $Z = 124$, $A = 301$–312 decay chain calculated by the UDL formula and GLDM to α-decay half-lives and two formulas to spontaneous fission half-lives.

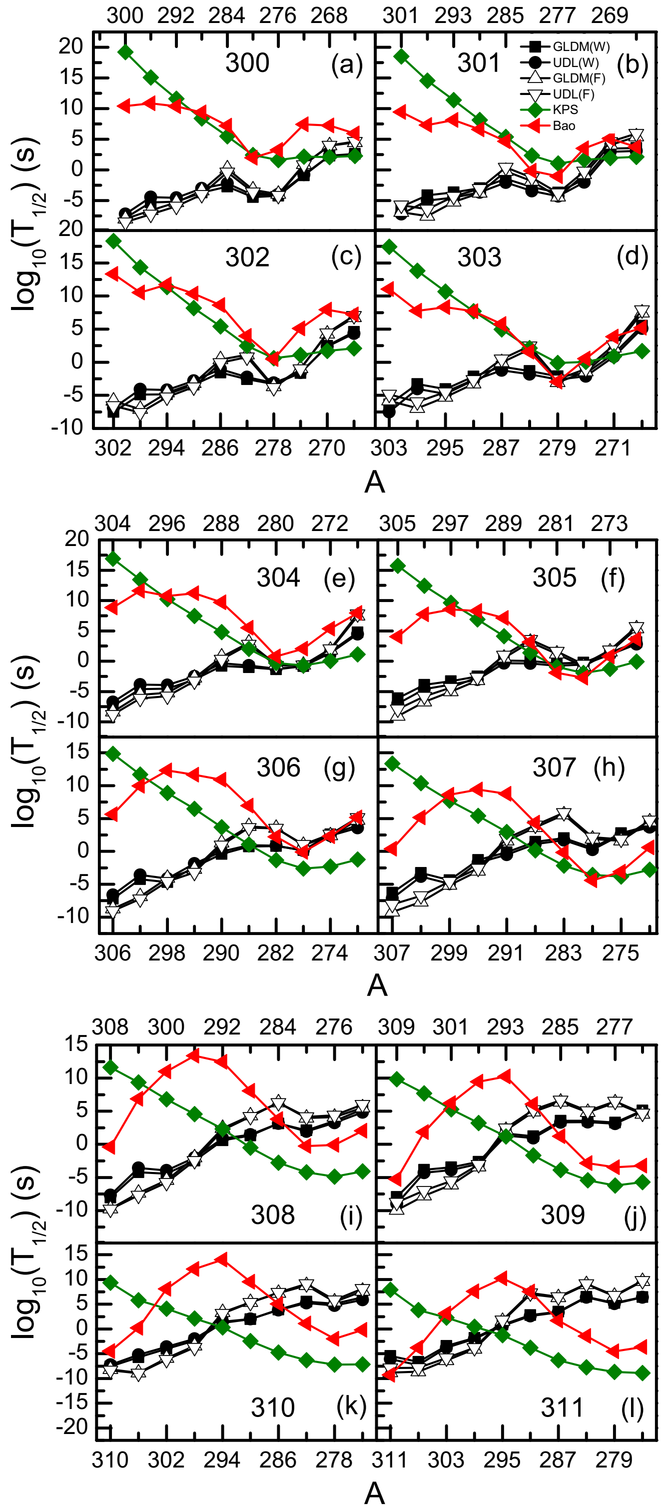

FIG. 2. $Z = 123$, $A = 300$–311 decay chain calculated by the UDL formula and GLDM to α-decay half-lives and two formulas to spontaneous fission half-lives..

detect new SHN. In Table III, we list the α-decay half-lives by the UDL formula and GLDM. Spontaneous fission half-lives of the isotopes of $Z = 118$–124 are also predicted.

IV. SUMMARY

In general, this paper used the UDL formula and GLDM to calculate $Z = 104$–124 half-lives for α decay. The decay

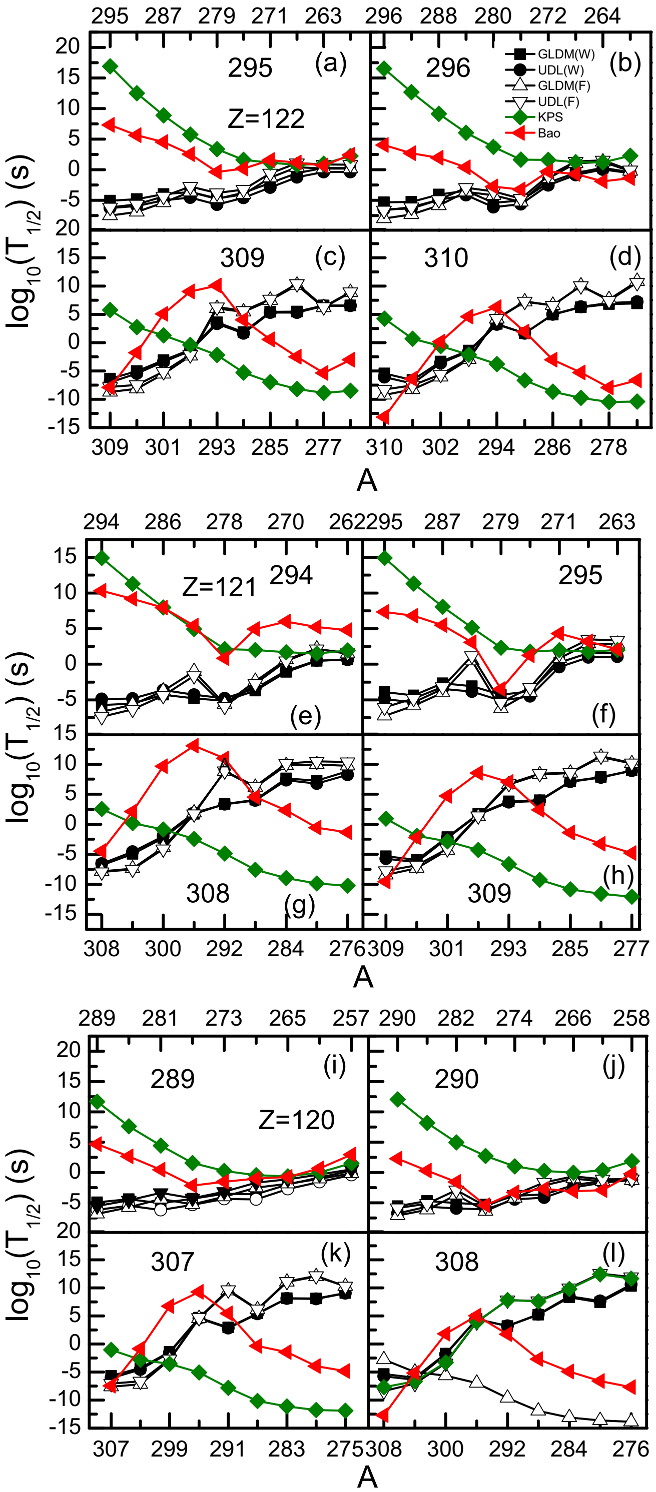

FIG. 3. $^{295,296,309,310}122$, $^{294,295,308,309}121$, and $^{289,290,307,308}120$ decay chains calculated by the UDL formula and GLDM to α-decay half-lives and two formulas to spontaneous fission half-lives.

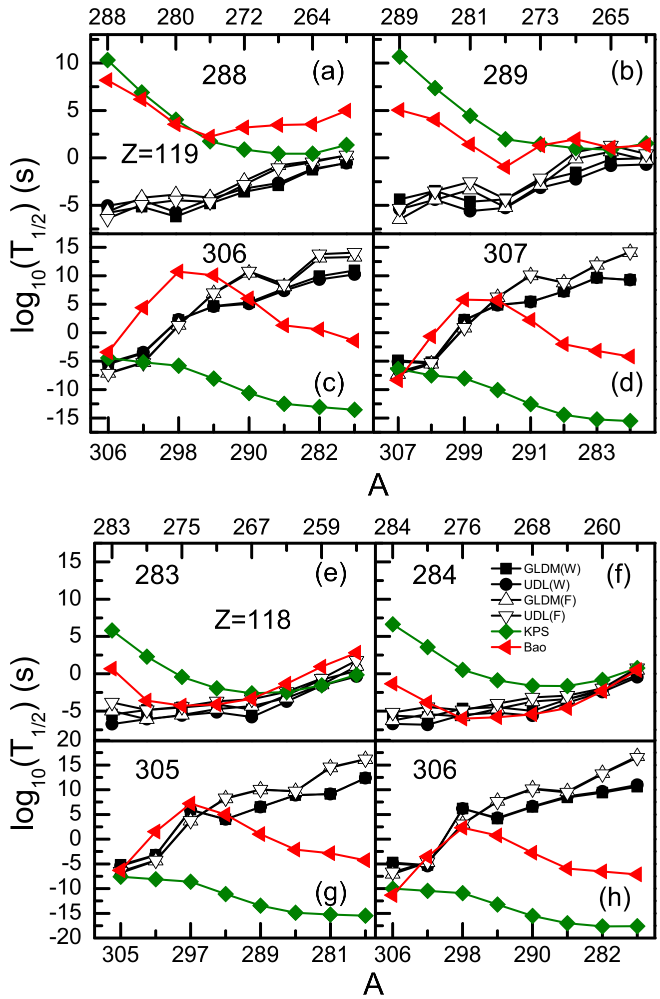

FIG. 4. $^{288,289,306,307}119$ and $^{283,284,305,306}118$ decay chains calculated by the UDL formula and GLDM to α-decay half-lives and two formulas to spontaneous fission half-lives.

energy Q_α chosen in computation comes from four different mass tables. Then we calculated spontaneous fission half-lives by three different formulas. We find that the consideration of the isospin effect is important and requires reasonable consideration for the calculation of spontaneous fission half-lives. The experimental data are well reproduced by the generalized Swiatecki's formulas when considering isospin effect. Decay modes of the isotopes of $Z = 118$–124 are predicted, which will be helpful for identification of these SHN in future experiments.

ACKNOWLEDGMENTS

The work is supported by the National Natural Science Foundation of China (Grants No. 11705055, No. 11475050, and No. 11175074). Project supported by the Science and Technology Plan of Hunan Province, China (Grant No. 2018JJ3324) and Excellent Youth Fund of Hunan Provincial Education Department (Grant No. 17B154).

TABLE III. Predicted α-decay and spontaneous fission half-lives for SHN $Z = 118$–124.

A	$\log_{10}(T_{1/2}^{\alpha})$ (Cal.)							$\log_{10}(T_{1/2}^{SF})$(Cal.)
	Q_α (WS)	Q_α (FRDM)	E_{shell}	UDL (WS)	UDL (FRDM)	GLDM (WS)	GLDM (FRDM)	Bao
$Z = 124$								
301	15.012	15.265	− 5.40	− 7.963	− 8.390	− 6.557	− 6.932	7.676
302	14.811	13.885	− 5.36	− 8.085	− 6.389	− 6.638	− 5.131	8.836
303	14.889	13.455	− 5.43	− 7.784	− 5.105	− 6.469	− 4.077	12.760
304	15.016	13.635	− 4.24	− 8.475	− 5.935	− 7.146	− 4.862	10.464
305	14.902	13.435	− 4.30	− 7.842	− 5.099	− 6.708	− 4.231	14.209
306	14.819	16.325	− 3.79	− 8.168	− 10.610	− 6.939	− 9.032	0.176
307	14.807	16.055	− 3.69	− 7.709	− 9.761	− 6.673	− 8.437	1.746
308	14.794	16.135	− 3.04	− 8.158	− 10.355	− 6.984	− 8.864	− 3.784
309	15.331	16.485	− 3.35	− 8.635	− 10.447	− 7.528	− 9.053	− 3.748
310	15.540	16.325	− 2.66	− 9.449	− 10.678	− 8.155	− 9.173	− 8.684
311	14.773	15.505	− 2.77	− 7.717	− 8.955	− 6.799	− 7.886	− 7.242
312	13.891	15.295	− 2.59	− 6.568	− 9.079	− 5.667	− 7.888	− 11.922
$Z = 123$								
300	14.703	15.155	− 5.83	− 7.222	− 7.996	− 7.860	− 8.533	10.421
301	14.434	14.265	− 5.38	− 7.216	− 6.909	− 6.036	− 5.764	9.448
302	14.519	13.935	− 5.57	− 6.932	− 5.857	− 7.524	− 6.565	13.333
303	14.588	13.675	− 5.20	− 7.525	− 5.827	− 6.366	− 4.852	11.063
304	14.393	15.325	− 5.24	− 6.740	− 8.346	− 7.369	− 8.781	8.852
305	14.280	15.475	− 4.74	− 7.004	− 9.062	− 6.081	− 7.880	4.034
306	14.313	15.535	− 4.65	− 6.627	− 8.722	− 7.198	− 9.027	5.661
307	14.330	15.545	− 4.00	− 7.128	− 9.208	− 6.263	− 8.078	0.388
308	14.890	16.165	− 3.20	− 7.682	− 9.741	− 8.055	− 9.809	− 0.400
309	15.382	15.985	− 2.43	− 8.977	− 9.936	− 7.951	− 8.764	− 5.249
310	14.613	15.145	− 3.22	− 7.233	− 8.148	− 7.586	− 8.374	− 4.498
311	13.736	15.275	− 3.05	− 6.080	− 8.835	− 5.468	− 7.899	− 9.296
$Z = 122$								
295	13.844	14.505	− 6.03	− 6.298	− 7.510	− 5.095	− 6.166	7.301
296	13.705	14.505	− 5.53	− 6.502	− 7.981	− 5.334	− 6.654	4.016
297	13.670	14.805	− 5.85	− 5.997	− 8.068	− 4.923	− 6.772	6.772
298	13.650	14.915	− 5.53	− 6.430	− 8.727	− 5.339	− 7.369	3.677
299	13.446	14.995	− 6.25	− 5.594	− 8.426	− 4.626	− 7.142	6.587
300	13.115	13.985	− 5.73	− 5.393	− 7.102	− 4.429	− 5.984	5.302
301	13.142	13.895	− 5.96	− 5.013	− 6.497	− 4.160	− 5.508	8.806
302	13.234	14.045	− 5.57	− 5.671	− 7.248	− 4.746	− 6.173	4.937
303	12.964	14.705	− 5.66	− 4.678	− 7.997	− 3.920	− 6.905	5.992
304	12.742	14.815	− 5.17	− 4.676	− 8.658	− 3.949	− 7.568	1.195
305	12.933	14.935	− 5.10	− 4.647	− 8.426	− 4.047	− 7.475	2.875
306	13.068	14.925	− 4.46	− 5.398	− 8.879	− 4.699	− 7.831	− 2.210
307	13.820	15.575	− 3.64	− 6.455	− 9.511	− 5.801	− 8.465	− 3.116
308	14.653	15.445	− 2.87	− 8.445	− 9.773	− 7.516	− 8.645	− 8.084
309	14.100	15.055	− 3.38	− 7.014	− 8.695	− 6.356	− 7.831	− 7.892
310	13.377	15.105	− 3.20	− 6.094	− 9.249	− 5.444	− 8.246	− 13.149
$Z = 121$								
294	13.215	14.155	− 6.46	− 4.880	− 6.683	− 5.730	− 7.365	10.296
295	12.984	14.205	− 6.47	− 4.878	− 7.244	− 3.916	− 6.055	7.344
296	12.994	14.095	− 6.78	− 4.462	− 6.607	− 5.295	− 7.240	10.869
297	13.041	14.355	− 6.47	− 5.029	− 7.548	− 4.146	− 6.428	7.292
298	12.806	14.345	− 6.63	− 4.101	− 7.094	− 4.890	− 7.604	10.531
299	12.551	14.015	− 6.57	− 4.023	− 6.965	− 3.282	− 5.979	7.782
300	12.674	13.495	− 6.80	− 3.853	− 5.538	− 4.582	− 6.141	11.611
301	12.803	13.855	− 6.44	− 4.599	− 6.700	− 3.896	− 5.813	7.729
302	12.531	14.175	− 6.51	− 3.577	− 6.855	− 4.243	− 7.245	9.951
303	12.437	14.375	− 6.00	− 3.842	− 7.686	− 3.260	− 6.760	5.172
304	12.503	14.445	− 5.94	− 3.550	− 7.373	− 4.217	− 7.703	6.868

TABLE III. (*Continued*).

A	$\log_{10}(T^{\alpha}_{1/2})$ (Cal.)							$\log_{10}(T^{SF}_{1/2})$(Cal.)
	Q_α (WS)	Q_α (FRDM)	E_{shell}	UDL (WS)	UDL (FRDM)	GLDM (WS)	GLDM (FRDM)	Bao
305	12.632	14.395	− 5.31	− 4.300	− 7.755	− 3.838	− 6.991	1.833
306	13.291	15.305	− 4.48	− 5.235	− 8.863	− 5.711	− 8.929	0.198
307	14.124	14.885	− 3.72	− 7.300	− 8.638	− 6.662	− 7.844	− 3.810
308	13.958	14.665	− 3.79	− 6.556	− 7.825	− 6.833	− 7.967	− 4.484
309	13.300	14.755	− 3.60	− 5.756	− 8.450	− 5.339	− 7.749	− 9.560
$Z = 120$								
289	13.540	13.885	− 6.19	− 6.175	− 6.830	− 4.945	− 5.525	4.655
290	13.593	13.775	− 6.20	− 6.749	− 7.095	− 5.561	− 5.870	2.268
291	13.410	13.915	− 6.41	− 5.957	− 6.920	− 4.816	− 5.680	5.615
292	13.380	13.885	− 6.47	− 6.369	− 7.335	− 5.274	− 6.144	2.671
293	13.272	13.685	− 6.90	− 5.720	− 6.522	− 4.671	− 5.393	6.914
294	13.052	13.295	− 6.93	− 5.747	− 6.236	− 4.827	− 5.267	4.594
295	13.134	13.355	− 7.23	− 5.476	− 5.918	− 4.580	− 4.979	8.244
296	13.241	13.685	− 6.92	− 6.162	− 7.027	− 5.276	− 6.073	3.946
297	13.103	13.535	− 7.03	− 5.448	− 6.303	− 4.649	− 5.435	7.577
298	12.808	13.355	− 7.05	− 5.310	− 6.422	− 4.562	− 5.577	4.679
299	13.051	13.105	− 7.07	− 5.377	− 5.486	− 4.658	− 4.758	8.391
300	13.308	13.395	− 6.72	− 6.362	− 6.535	− 5.582	− 5.744	4.357
301	12.938	13.665	− 6.74	− 5.177	− 6.620	− 4.546	− 5.865	6.832
302	12.765	13.715	− 6.29	− 5.286	− 7.186	− 4.644	− 6.378	2.135
303	12.645	13.845	− 6.25	− 4.594	− 6.993	− 4.084	− 6.270	3.946
304	12.480	13.825	− 5.62	− 4.708	− 7.426	− 4.234	− 6.740	− 1.076
305	13.041	14.475	− 4.78	− 5.456	− 8.165	− 5.034	− 7.477	− 1.787
306	13.687	14.265	− 4.02	− 7.198	− 8.264	− 6.598	− 7.548	− 6.426
307	13.339	14.145	− 3.68	− 6.087	− 7.612	− 5.688	− 7.062	− 7.462
308	12.956	14.305	− 3.47	− 5.784	− 8.369	− 5.367	− 7.698	− 12.698
$Z = 119$								
288	13.059	13.385	− 6.56	− 5.042	− 5.689	− 5.803	− 6.403	8.174
289	13.013	13.545	− 6.67	− 5.420	− 6.469	− 4.364	− 5.330	5.037
290	12.925	13.365	− 7.16	− 4.803	− 5.685	− 5.511	− 6.337	9.153
291	12.965	13.205	− 7.16	− 5.356	− 5.840	− 4.380	− 4.833	6.807
292	12.784	13.165	− 7.60	− 4.545	− 5.324	− 5.198	− 5.927	10.363
293	12.550	12.885	− 7.57	− 4.522	− 5.226	− 3.682	− 4.333	8.132
294	12.600	12.805	− 7.91	− 4.192	− 4.624	− 4.848	− 5.252	11.735
295	12.661	12.885	− 7.62	− 4.792	− 5.260	− 4.057	− 4.498	8.334
296	12.459	13.075	− 7.75	− 3.922	− 5.211	− 4.540	− 5.745	10.766
297	12.209	12.745	− 7.81	− 3.841	− 5.003	− 3.274	− 4.356	8.526
298	12.549	12.505	− 7.83	− 4.150	− 4.055	− 4.682	− 4.593	12.321
299	12.695	12.795	− 7.49	− 4.931	− 5.141	− 4.369	− 4.569	8.605
300	12.443	13.145	− 7.54	− 3.955	− 5.419	− 4.426	− 5.785	10.992
301	12.196	13.265	− 7.04	− 3.879	− 6.128	− 3.448	− 5.544	6.205
302	12.263	13.375	− 7.01	− 3.591	− 5.908	− 4.007	− 6.164	8.096
303	12.141	13.375	− 6.40	− 3.790	− 6.378	− 3.437	− 5.843	3.117
304	12.711	14.145	− 5.54	− 4.595	− 7.381	− 4.943	− 7.490	2.111
305	13.318	13.845	− 4.80	− 6.300	− 7.305	− 5.928	− 6.842	− 2.216
306	13.033	13.965	− 3.70	− 5.294	− 7.088	− 5.531	− 7.161	− 3.414
307	12.708	13.815	− 3.39	− 5.092	− 7.282	− 4.883	− 6.904	− 8.340
$Z = 118$								
283	13.602	12.705	− 5.53	− 6.755	− 4.976	− 5.464	− 3.829	0.676
284	13.337	13.095	− 5.66	− 6.719	− 6.243	− 5.600	− 5.169	− 1.350
285	12.948	13.065	− 6.12	− 5.511	− 5.747	− 4.407	− 4.618	2.627
286	12.792	13.045	− 6.25	− 5.663	− 6.178	− 4.696	− 5.160	0.278
287	12.689	12.875	− 6.70	− 5.011	− 5.397	− 4.013	− 4.366	4.505
288	12.438	12.875	− 6.79	− 4.949	− 5.868	− 4.095	− 4.953	1.932
289	12.487	12.755	− 7.22	− 4.619	− 5.184	− 3.741	− 4.268	5.901

TABLE III. (*Continued*).

A	$\log_{10}(T^{\alpha}_{1/2})$ (Cal.)							$\log_{10}(T^{SF}_{1/2})$(Cal.)
	Q_α (WS)	Q_α (FRDM)	E_{shell}	UDL (WS)	UDL (FRDM)	GLDM (WS)	GLDM (FRDM)	Bao
290	12.571	12.805	– 7.20	– 5.269	– 5.758	– 4.471	– 4.912	2.698
291	12.320	12.555	– 7.59	– 4.292	– 4.798	– 3.509	– 3.989	6.982
292	12.059	12.365	– 7.54	– 4.180	– 4.860	– 3.491	– 4.138	4.229
293	12.101	12.275	– 7.84	– 3.839	– 4.226	– 3.153	– 3.522	7.916
294	12.140	12.275	– 7.56	– 4.398	– 4.697	– 3.802	– 4.091	4.666
295	11.882	12.185	– 8.21	– 3.374	– 4.061	– 2.830	– 3.488	7.991
296	11.642	12.285	– 7.93	– 3.281	– 4.753	– 2.813	– 4.224	5.392
297	11.980	12.105	– 8.01	– 3.633	– 3.916	– 3.173	– 3.447	9.233
298	12.092	12.505	– 7.61	– 4.357	– 5.263	– 3.907	– 4.757	5.123
299	11.903	12.635	– 7.66	– 3.490	– 5.102	– 3.114	– 4.641	7.756
300	11.693	12.715	– 7.20	– 3.469	– 5.740	– 3.112	– 5.276	3.114
301	11.845	12.825	– 7.19	– 3.388	– 5.531	– 3.091	– 5.112	5.080
302	11.751	12.845	– 6.59	– 3.641	– 6.043	– 3.333	– 5.599	0.142
303	12.349	13.635	– 5.72	– 4.555	– 7.158	– 4.272	– 6.662	– 0.857
304	12.980	13.335	– 4.98	– 6.352	– 7.055	– 6.013	– 6.663	– 5.179
305	12.738	13.445	– 3.88	– 5.417	– 6.831	– 5.225	– 6.526	– 6.305
306	12.283	13.305	– 3.13	– 4.914	– 7.030	– 4.731	– 6.702	– 11.328

[1] S. Hofmann and G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
[2] S. Hofmann, Radiochim. Acta **99**, 405 (2011).
[3] K. Morita *et al.*, J. Phys. Soc. Jpn. **76**, 045001 (2007).
[4] Y. Oganessian, J. Phys. G: Nucl. Part. Phys. **34**, R165 (2007).
[5] Yu. Ts. Oganessian, F. S. Abdullin, P. D. Bailey, D. E. Benker, M. E. Bennett, S. N. Dmitriev, J. G. Ezold, J. H. Hamilton, R. A. Henderson, M. G. Itkis, Y. V. Lobanov, A. N. Mezentsev, K. J. Moody, S. L. Nelson, A. N. Polyakov, C. E. Porter, A. V. Ramayya, F. D. Riley, J. B. Roberto, M. A. Ryabinin, K. P. Rykaczewski, R. N. Sagaidak, D. A. Shaughnessy, I. V. Shirokovsky, M. A. Stoyer, V. G. Subbotin, R. Sudowe, A. M. Sukhov, Y. S. Tsyganov, V. K. Utyonkov, A. A. Voinov, G. K. Vostokin, and P. A. Wilk, Phys. Rev. Lett. **104**, 142502 (2010).
[6] Yu. Ts. Oganessian, Radiochim. Acta **99**, 429 (2011).
[7] W. D. Myers and W. J. Swiatecki, Nucl. Phys. **81**, 1 (1966).
[8] A. Sobiczewski, F. A. Gareev, and B. N. Kalinkin, Phys. Lett. **22**, 500 (1966).
[9] U. Mosel and W. Greiner, Z. Phys. **222**, 261 (1969).
[10] S. G. Nilsson, C. F. Tsang, A. Sobiczewski, Z. Szymanski, S. Wycech, C. Gustafson, I.-L. Lamm, P. Möller, and B. Nilsson, Nucl. Phys. A **131**, 1 (1969).
[11] M. Bender *et al.*, Phys. Lett. B **515**, 42 (2001).
[12] P. Ring, Prog. Part. Nucl. Phys. **37**, 193 (1996).
[13] S. Cwiok *et al.*, Nucl. Phys. A **611**, 211 (1996).
[14] E. O. Fiset and J. R. Nix, Nucl. Phys. A **193**, 647 (1972).
[15] P. Möller, J. R. Nix, and W. J. Swiatecki, Nucl. Phys. A **492**, 349 (1989).
[16] R. Smolánczuk, J. Skalski, and A. Sobiczewski, Phys. Rev. C **52**, 1871 (1995).
[17] R. Smolánczuk, Phys. Rev. C **56**, 812 (1997).
[18] A. Sobiczewski and K. Pomorski, Prog. Part. Nucl. Phys **58**, 292 (2007).
[19] Yu. Ts. Oganessian, V. K. Utyonkov, Y. V. Lobanov, F. S. Abdullin, A. N. Polyakov, I. V. Shirokovsky, Y. S. Tsyganov, G. G. Gulbekian, S. L. Bogomolov, B. N. Gikal, A. N. Mezentsev, S. Iliev, V. G. Subbotin, A. M. Sukhov, A. A. Voinov, G. V. Buklanov, K. Subotic, V. I. Zagrebaev, M. G. Itkis, J. B. Patin, K. J. Moody, J. F. Wild, M. A. Stoyer, N. J. Stoyer, D. A. Shaughnessy, J. M. Kenneally, P. A. Wilk, R. W. Lougheed, R. I. Ilkaev, and S. P. Vesnovskii, Phys. Rev. C **70**, 064609 (2004).
[20] Yu. Ts. Oganessian, V. K. Utyonkov, Y. V. Lobanov, F. S. Abdullin, A. N. Polyakov, R. N. Sagaidak, I. V. Shirokovsky, Y. S. Tsyganov, A. A. Voinov, G. G. Gulbekian, S. L. Bogomolov, B. N. Gikal, A. N. Mezentsev, V. G. Subbotin, A. M. Sukhov, K. Subotic, V. I. Zagrebaev, G. K. Vostokin, M. G. Itkis, R. A. Henderson, J. M. Kenneally, J. H. Landrum, K. J. Moody, D. A. Shaughnessy, M. A. Stoyer, N. J. Stoyer, and P. A. Wilk, Phys. Rev. C **76**, 011601(R) (2007).
[21] Yu. Ts. Oganessian, V. K. Utyonkov, Y. V. Lobanov, F. S. Abdullin, A. N. Polyakov, I. V. Shirokovsky, Y. S. Tsyganov, G. G. Gulbekian, S. L. Bogomolov, B. N. Gikal, A. N. Mezentsev, S. Iliev, V. G. Subbotin, A. M. Sukhov, A. A. Voinov, G. V. Buklanov, K. Subotic, V. I. Zagrebaev, M. G. Itkis, J. B. Patin, K. J. Moody, J. F. Wild, M. A. Stoyer, N. J. Stoyer, D. A. Shaughnessy, J. M. Kenneally, P. A. Wilk, R. W. Lougheed, R. I. Ilkaev, and S. P. Vesnovskii, Phys. Rev. C **69**, 054607 (2004).
[22] Yu. Ts. Oganessian, F. S. Abdullin, S. N. Dmitriev, J. M. Gostic, J. H. Hamilton, R. A. Henderson, M. G. Itkis, K. J. Moody, A. N. Polyakov, A. V. Ramayya, J. B. Roberto, K. P. Rykaczewski, R. N. Sagaidak, D. A. Shaughnessy, I. V. Shirokovsky, M. A. Stoyer, N. J. Stoyer, V. G. Subbotin, A. M. Sukhov, Y. S. Tsyganov, V. K. Utyonkov, A. A. Voinov, and G. K. Vostokin, Phys. Rev. C **87**, 014302 (2013).
[23] Yu. Ts. Oganessian, V. K. Utyonkov, Y. V. Lobanov, F. S. Abdullin, A. N. Polyakov, R. N. Sagaidak, I. V. Shirokovsky, Y. S. Tsyganov, A. A. Voinov, G. G. Gulbekian, S. L. Bogomolov, B. N. Gikal, A. N. Mezentsev, S. Iliev, V. G. Subbotin, A. M. Sukhov, K. Subotic, V. I. Zagrebaev, G. K. Vostokin, M. G. Itkis, K. J. Moody, J. B. Patin, D. A. Shaughnessy, M. A. Stoyer,

N. J. Stoyer, P. A. Wilk, J. M. Kenneally, J. H. Landrum, J. F. Wild, and R. W. Lougheed, Phys. Rev. C **74**, 044602 (2006).
[24] J. M. Gates, M. A. Garcia, K. E. Gregorich *et al.*, Phys. Rev. C **77**, 034603 (2008).
[25] F. P. Heßberger, S. Antalic, D. Ackermannet *et al.*, Eur. Phys. J. A **52**, 328 (2016).
[26] J. Dvorak, W. Brüchle, M. Chelnokov *et al.*, Phys. Rev. Lett. **100**, 132503 (2008).
[27] H. Haba, D. Kaji, H. Kikunaga *et al.*, Phys. Rev. C **83**, 034602 (2011).
[28] H. Haba, D. Kaji, Y. Kudou *et al.*, Phys. Rev. C **85**, 024611 (2012).
[29] K. Varga, R. G. Lovas, and R. J. Liotta, Phys. Rev. Lett **69**, 37 (1992).
[30] B. Buck, A. C. Merchant, and S. M. Perez, Phys. Rev. C **51**, 559 (1995).
[31] G. Royer, J. Phys. G: Nucl. Part. Phys. **26**, 1149 (2000).
[32] P. Mohr, Phys. Rev. C **73**, 031301 (2006).
[33] C. Xu and Z. Ren, Phys. Rev. C **74**, 014304 (2006).
[34] D. N. Poenaru, I. H. Plonski, and W. Greiner, Phys. Rev. C **74**, 014312 (2006).
[35] J. C. Pei, F. R. Xu, Z. J. Lin, and E. G. Zhao, Phys. Rev. C **76**, 044326 (2007).
[36] M. Ismail, A. Y. Ellithi, M. M. Botros, and A. Adel, Phys. Rev. C **81**, 024602 (2010).
[37] S. B. Duarte and N. Teruya, Phys. Rev. C **85**, 017601 (2012).
[38] Y. Z. Wang, S. J. Wang, Z. Y. Hou, and J. Z. Gu, Phys. Rev. C **92**, 064301 (2015).
[39] O. N. Ghodsi and A. Daei-Ataollah, Phys. Rev. C **93**, 024612 (2016).
[40] X. D. Sun, P. Guo, and X.-H. Li, Phys. Rev. C **93**, 034316 (2016).
[41] H. F. Zhang and G. Royer, Phys. Rev. C **77**, 054318 (2008).
[42] D. D. Ni and Z. Z. Ren, Phys. Rev. C **80**, 051303(R) (2009); **81**, 064318 (2010).
[43] X. J. Bao, H. F. Zhang, H. F. Zhang *et al.*, Nucl. Phys. A **921**, 85 (2014).
[44] V. E. Viola, Jr., G. T. Seaborg, J. Inorg. Nucl. Chem. **28**, 741 (1966).
[45] A. Sobiczewski, Z. Patyk, and S. Cwiok, Phys. Lett. B **224**, 1 (1989).
[46] Z. Z. Ren, C. Xu, and Z. J. Wang, Phys. Rev. C **70**, 034304 (2004).
[47] A. Parkhomenko and A. Sobiczewski, Acta Phys. Pol. B **36**, 3095 (2005).
[48] C. Qi, F. R. Xu, R. J. Liotta, and R. Wyss, Phys. Rev. Lett **103**, 072501 (2009).
[49] D. D. Ni, Z. Z. Ren, T. K. Dong, and C. Xu, Phys. Rev. C **78**, 044310 (2008).
[50] B. Sahu, Phys. Rev. C **78**, 044608 (2008).
[51] Y. J. Ren and Z. Z. Ren, Phys. Rev. C **85**, 044608 (2012).
[52] A. I. Budaca and I. Silisteanu, Phys. Rev. C **88**, 044618 (2013).
[53] T. K. Dong and Z. Z. Ren, Phys. Rev. C **82**, 034320 (2010).
[54] N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).
[55] W. Swiatecki, Phys. Rev **100**, 937 (1955).
[56] J. Randrup, C. F. Tsang, P. Möller, S. G. Nilsson, and S. E. Larsson, Nucl. Phys. A **217**, 221 (1973).
[57] J. Randrup, S. E. Larsson, P. Möller, S. G. Nilsson, K. Pomorski, and A. Sobiczewski, Phys. Rev. C **13**, 229 (1976).
[58] M. Kowal, P. Jachimowicz, and A. Sobiczewski, Phys. Rev. C **82**, 014303 (2010).
[59] M. Warda and J. L. Egido, Phys. Rev. C **86**, 014322 (2012).
[60] A. Staszczak, A. Baran, and W. Nazarewicz, Phys. Rev. C **87**, 024320 (2013).
[61] P. R. Chowdhury, C. Samanta, and D. N. Basu, Phys. Rev. C **77**, 044603 (2008).
[62] D. N. Poenaru, R. A. Gherghescu, and W. Greiner, J. Phys. G: Nucl. Part. Phys. **40**, 105105 (2013).
[63] A. Baran, Z. Lojewski, K. Sieja, and M. Kowal, Phys. Rev. C **72**, 044310 (2005).
[64] A. Sobiczewski, Acta Phys. Pol. B **42**, 1871 (2011).
[65] P. Möller and J. R. Nix, Nucl. Phys. A **296**, 289 (1978).
[66] A. Baran, K. Pomorski, A. Lukasiak, and A. Sobiczewski, Nucl. Phys. A **361**, 83 (1981).
[67] S. Cwiok, V. V. Pashkevich, J. Dudek, and W. Nazarewicz, Nucl. Phys. A **410**, 254 (1983).
[68] P. Möller, G. A. Leander, and J. R. Nix, Z. Phys. A **323**, 41 (1986).
[69] Z. Patyk and A. Sobiczewski, Phys. Lett. B **256**, 307 (1991).
[70] C. Xu and Z. Ren, Phys. Rev. C **71**, 014309 (2005).
[71] C. Xu, Z. Ren, and Y. Guo, Phys. Rev. C **78**, 044329 (2008).
[72] A. V. Karpov, V. I. Zagrebaev, Y. Martinez Palenzuela, L. Felipe Ruiz, and W. Greiner, Int. J. Mod. Phys. E **21**, 1250013 (2012).
[73] X. J. Bao, S. Q. Guo, H. F. Zhang, Y. Z. Xing, J. M. Dong, and J. Q. Li, J. Phys. G **42**, 085101 (2015).
[74] K. P. Santhosh and C. Nithya, Phys. Rev. C **94**, 054621 (2016).
[75] D. N. Poenaru and R. A. Gherghescu, Phys. Rev. C **94**, 014309 (2016).
[76] S. E. Agbemava, A. V. Afanasjev, D. Ray, and P. Ring, Phys. Rev. C **95**, 054324 (2017).
[77] Y. B. Qian and Z. Z. Ren, Eur. Phys. J. A **49**, 5 (2013).
[78] K. P. Santhosh, S. Sabina, and G. J. Jayesh, Nucl. Phys. A **850**, 34 (2011).
[79] K. P. Santhosh, B. Priyanka, and M. S. Unnikrishnan, Phys. Rev. C **85**, 034604 (2012).
[80] K. P. Santhosh and B. Priyanka, J. Phys. G: Nucl. Part. Phys. **39**, 085106 (2012).
[81] Y. B. Qian and Z. Z. Ren, Phys. Rev. C **90**, 064308 (2014).
[82] G. Royer and B. Remaud, J. Phys. G **10**, 1541 (1984).
[83] G. Royer and F. Haddad, Phys. Rev. C **51**, 2813 (1995).
[84] G. Royer and K. Zbiri, Nucl. Phys. A **697**, 630 (2002).
[85] X. J. Bao, S. Q. Guo, H. F. Zhang, and J. Q. Li, Phys. Rev. C **95**, 034323 (2017).
[86] T. L. Zhao, X. J. Bao, and S. Q. Guo, J. Phys. G: Nucl. Part. Phys. **45**, 025106 (2018).
[87] H. F. Zhang, G. Royer, Y. J. Wang, J. M. Dong, W. Zuo, and J. Q. Li, Phys. Rev. C **80**, 057301 (2009).
[88] G. Royer and B. Remaud, Nucl. Phys. A **444**, 477 (1985).
[89] D. L. Hill and J. A. Wheeler, Phys. Rev. **89**, 1102 (1953).
[90] V. E. Viola, Jr., B. D. Wilkins, Nucl. Phys. A **82**, 65 (1966).
[91] P. Möller, J. Nix, W. Myers, and W. Swiatecki, At. Data Nucl. Data Tables **59**, 185 (1995).

[92] K. Siwek-Wilczynska, I. Skwira, and J. Wilczynski, Phys. Rev. C **72**, 034605 (2005).
[93] P. Möller, A. J. Sierk, T. Ichikawa, and H. Sagawa, At. Data Nucl. Data Tables **109**, 1 (2016).
[94] P. Jachimowicz, M. Kowal, and J. Skalski, Phys. Rev. C **89**, 024304 (2014).
[95] M. Liu, N. Wang, Y. Deng, and X. Wu, Phys. Rev. C **84**, 014333 (2011).
[96] H. Koura, T. Tachibana, M. Uno, and M. Yamada, Prog. Theor. Phys. **113**, 305 (2005).
[97] Yu. Ts. Oganessian, A. Sobiczewski, and G. M. Ter-Akopian, Phys. Scr. **92**, 023003 (2017).