PHYSICAL REVIEW C **98**, 024625 (2018)

α-decay half-lives of superheavy nuclei from a modified generalized liquid-drop model

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(Received 4 July 2018; published 28 August 2018)

The α-decay half-lives of superheavy nuclei are studied using the generalized liquid-drop model (GLDM) with 1977 nuclear proximity potential proposed by Blocki *et al.* [Ann. Phys. (NY) **105**, 427 (1977)]. The result obtained with the present formalism is compared with the experimental half-lives and half-lives using GLDM. The standard deviation of the present approach is found to be 0.34, which is less than that of GLDM of Royer (0.56). The study is extended to predict the α half-lives of some of the unknown isotopes in superheavy region. We hope that the predictions on the α-decay half-lives using the present formalism may be helpful in future investigations in this field.

DOI: 10.1103/PhysRevC.98.024625

I. INTRODUCTION

Superheavy nuclei and their decay properties are one of the main topics of interest among the nuclear physicists. The search for superheavy nuclei was begun in the late 1960s with the prediction of magic island or island of stability [1–5]. Elements with $Z > 104$, which exist solely due to the shell effects, are referred to as superheavy elements. Two types of fusion reactions, the cold fusion reaction [6] and the hot fusion reaction [7] are used for the synthesis of superheavy elements.

α-decay and spontaneous fission are the main decay modes of most of the experimentally observed superheavy nuclei. So, the studies on α and spontaneous fission half-lives received much attention in this field. Different theoretical models have been put forward for studying the different aspects of these decay modes [8–16].

The generalized liquid-drop model (GLDM) developed by Royer in 1984 is one among the various theoretical models which are widely used for decay studies [17–22]. The GLDM consists of conventional liquid-drop model with the inclusion of nuclear proximity energy and quasi-molecular shape. GLDM can be used successfully to describe the nuclear fusion, fission, cluster decay, α-decay, and proton emission process.

In the present paper, the GLDM of Royer [23] has been modified by incorporating the nuclear proximity potential proposed by Blocki *et al.* [24,25]. Proximity 77 is found to be more effective in describing the α-decay than the other versions of proximity potentials [26,27]. α-decay half-lives of all the experimentally synthesized superheavy nuclei have been reproduced using the present method. Predictions on the α half-lives of some of the unknown superheavy nuclei are also performed.

The paper is organized as follows. The theoretical model used for the study is presented in Sec. II. The results and discussions are included in Sec. III. Section IV gives the summary of the entire work.

II. GENERALIZED LIQUID-DROP MODEL WITH 1977 PROXIMITY POTENTIAL

In GLDM, for a deformed nucleus, the macroscopic energy is defined as

$$E = E_V + E_S + E_C + E_R + E_P. \tag{1}$$

Here the terms E_V, E_S, E_C, E_R, and E_P represent the volume, surface, Coulomb, rotational, and proximity energy terms, respectively.

For the prescission region the volume, surface, and Coulomb energies in MeV are given by

$$E_V = -15.494(1 - 1.8I^2)A, \tag{2}$$

$$E_S = 17.9439(1 - 2.6I^2)A^{2/3}\left(S/4\pi R_0^2\right), \tag{3}$$

$$E_C = 0.6e^2(Z^2/R_0) \times 0.5 \int (V(\theta)/V_0) \times (R(\theta)/R_0)^3 \sin\theta\, d\theta. \tag{4}$$

Here I is the relative neutron excess and S the surface of the deformed nucleus, $V(\theta)$ is the electrostatic potential at the surface and V_0 the surface potential of the sphere.

For the post-scission region,

$$E_V = -15.494\left[\left(1 - 1.8I_1^2\right)A_1 + \left(1 - 1.8I_2^2\right)A_2\right], \tag{5}$$

$$E_S = 17.9439\left[\left(1 - 2.6I_1^2\right)A_1^{2/3} + \left(1 - 2.6I_2^2\right)A_2^{2/3}\right], \tag{6}$$

$$E_C = \frac{0.6e^2Z_1^2}{R_1} + \frac{0.6e^2Z_2^2}{R_2} + \frac{e^2Z_1Z_2}{r}. \tag{7}$$

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Here A_i, Z_i, R_i, and I_i are the masses, charges, radii, and relative neutron excess of the fragments, r is the distance between the centers of the fragments.

The nuclear proximity potential E_P is given by Blocki *et al.* [24] as

$$E_p(z) = 4\pi\gamma b\left[\frac{C_1C_2}{(C_1+C_2)}\right]\Phi\left(\frac{z}{b}\right), \tag{8}$$

with the nuclear surface tension coefficient,

$$\gamma = 0.9517[1 - 1.7826(N-Z)^2/A^2] \quad \text{MeV/fm}^2, \tag{9}$$

where N, Z, and A represent neutron, proton, and mass number of parent nucleus, respectively, Φ represents the universal proximity potential [25] given as

$$\Phi(\varepsilon) = -4.41e^{-\varepsilon/0.7176}, \quad \text{for } \varepsilon > 1.9475, \tag{10}$$

$$\Phi(\varepsilon) = -1.7817 + 0.9270\varepsilon + 0.01696\varepsilon^2 - 0.05148\varepsilon^3, \quad \text{for} \quad 0 \leqslant \varepsilon \leqslant 1.9475, \tag{11}$$

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

$$C_i = R_i - \left(\frac{b^2}{R_i}\right). \tag{12}$$

For R_i we use semiempirical formula in terms of mass number A_i as [24]

$$R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}. \tag{13}$$

The barrier penetrability P is calculated with the action integral

$$P = \exp\left\{-\frac{2}{\hbar}\int_{R_{\text{in}}}^{R_{\text{out}}}\sqrt{2B(r)[E(r) - E(\text{sphere})]}dr\right\}, \tag{14}$$

where $R_{\text{in}} = R_1 + R_2$, $B(r) = \mu$ and $R_{\text{out}} = e^2Z_1Z_2/Q$. R_1, R_2 are the radius of the daughter nuclei and emitted α particle, respectively, and μ the reduced mass and Q the released energy.

The partial half-life is related to the decay constant λ by

$$T_{1/2} = \left(\frac{\ln 2}{\lambda}\right) = \left(\frac{\ln 2}{\nu P}\right). \tag{15}$$

The assault frequency ν has been taken as 10^{20} s^{-1}.

III. RESULTS AND DISCUSSION

The α-decay half-lives of superheavy nuclei are investigated with modified GLDM. The GLDM proposed by Royer is proved to be very successful for describing the half-lives of various decay modes [17–22]. In the present paper, the GLDM proposed by Royer, which considers the proximity function with parameterization of Feldmeir *et al.* [28] have been modified by using the proximity 77 proposed by Blocki *et al.* [24].

It was found that by incorporating the proximity potential of Blocki *et al.* [24] in GLDM, the formula can be improved well. The half-lives of all the experimentally synthesized superheavy nuclei are reproduced with good accuracy using the present method. Table I gives the comparison of experimental half-lives and half-lives predicted with the present method for various superheavy nuclei. The half-lives using GLDM [22] are also given. The experimental Q values and half-lives are taken from Oganessian *et al.* [29,30]. From the table it is evident that the present method can reproduce the experimental α half-lives of superheavy nuclei fairly well. The standard deviation of the

TABLE I. The comparison of α-decay half-lives using present method with experimental half-lives [29,30] and half-lives predicted by GLDM [22].

Z	A	N	Q Value (MeV)	$T_{1/2}^{\text{Expt}}$	$T_{1/2}^{\text{Present}}$	$T_{1/2}^{\text{GLDM}}$ [22]
118	294	176	11.81 ± 0.06	$1.8^{+75}_{-1.3}$ ms	$0.45^{+0.17}_{-0.12}$ ms	$0.15^{+0.05}_{-0.04}$ ms
116	293	177	10.67 ± 0.06	53^{+62}_{-19} ms	71^{+32}_{-22} ms	$22.81^{+10.22}_{-7.06}$ ms
116	292	176	10.80 ± 0.07	18^{+16}_{-6} ms	33^{+18}_{-12} ms	$10.45^{+5.65}_{-3.45}$ ms
116	291	175	10.89 ± 0.07	$6.3^{+11.6}_{-2.5}$ ms	20^{+11}_{-7} ms	$6.35^{+3.15}_{-2.08}$ ms
116	290	174	11.00 ± 0.08	15^{+26}_{-6} ms	11^{+7}_{-4} ms	$3.47^{+1.99}_{-1.26}$ ms
114	289	175	9.96 ± 0.06	$2.7^{+1.4}_{-0.7}$ s	$1.62^{+0.81}_{-0.53}$ ms	$0.52^{+0.25}_{-0.17}$ s
114	288	174	10.09 ± 0.07	$0.8^{+0.32}_{-0.18}$ s	$0.71^{+0.42}_{-0.26}$ s	$0.22^{+0.12}_{-0.08}$ s
114	287	173	10.16 ± 0.06	$0.51^{+0.18}_{-0.10}$ s	$0.46^{+0.23}_{-0.15}$ s	$0.16^{+0.08}_{-0.05}$ s
114	286	172	10.35 ± 0.06	$0.16^{+0.07}_{-0.03}$ s	$0.14^{+0.07}_{-0.04}$ s	$0.05^{+0.02}_{-0.02}$ s
112	285	173	9.29 ± 0.06	34^{+17}_{-9} s	$40^{+21.83}_{-14.43}$ s	$13.22^{+7.25}_{-4.64}$ s
112	283	171	9.67 ± 0.06	$4.0^{+1.3}_{-0.7}$ s	$2.85^{+1.48}_{-0.96}$ s	$0.95^{+0.48}_{-0.32}$ s
110	279	169	9.84 ± 0.06	$0.18^{+0.05}_{-0.03}$ s	$0.20^{+0.10}_{-0.06}$ s	$0.08^{+0.04}_{-0.02}$ s
108	275	167	9.44 ± 0.07	$0.15^{+0.27}_{-0.06}$ s	$0.67^{+0.43}_{-0.25}$ s	$0.27^{+0.16}_{-0.10}$ s
106	271	165	8.65 ± 0.08	$2.4^{+4.3}_{-1.0}$ min	$0.75^{+0.66}_{-0.34}$ min	$0.33^{+0.28}_{-0.16}$ min

TABLE II. The comparison of α-decay half-lives using present method with the experimental half-lives [31].

Z	A	N	Q Value (MeV)	$T_{1/2}^{\text{Expt}}$	$T_{1/2}^{\text{Present}}$
118	294	176	11.82 ± 0.06	$0.69^{+0.64}_{-0.22}$ ms	$0.43^{+0.16}_{-0.12}$ ms
117	294	177	11.18 ± 0.04	51^{+38}_{-16} ms	$0.71^{+0.18}_{-0.15}$ ms
117	293	176	11.32 ± 0.05	22^{+8}_{-4} ms	$0.33^{+0.11}_{-0.08}$ ms
116	293	177	10.71 ± 0.02	57^{+43}_{-17} ms	$56^{+7.1}_{-6.5}$ ms
116	292	176	10.78 ± 0.02	13^{+7}_{-4} ms	$38^{+4.9}_{-4.3}$ ms
116	291	175	10.89 ± 0.07	19^{+17}_{-6} ms	20^{+11}_{-7} ms
116	290	174	11.00 ± 0.07	$8.3^{+3.5}_{-1.9}$ ms	$11^{+5.7}_{-3.7}$ ms
115	290	175	10.41 ± 0.04	650^{+490}_{-200} ms	$185^{+53.9}_{-40.9}$ ms
115	289	174	10.49 ± 0.05	330^{+120}_{-80} ms	$117^{+42.5}_{-31.6}$ ms
115	288	173	10.65 ± 0.01	174^{+22}_{-18} ms	$45^{+2.9}_{-2.6}$ ms
115	287	172	10.76 ± 0.05	37^{+44}_{-13} ms	$24^{+8.6}_{-6.1}$ ms
114	289	175	9.98 ± 0.02	$1.9^{+0.7}_{-0.4}$ s	$1.4^{+0.2}_{-0.2}$ s
114	288	174	10.07 ± 0.03	$0.66^{+0.14}_{-0.10}$ s	$0.81^{+0.18}_{-0.14}$ s
114	287	173	10.17 ± 0.02	$0.48^{+0.14}_{-0.09}$ s	$0.44^{+0.06}_{-0.06}$ s
114	286	172	10.35 ± 0.04	$0.12^{+0.04}_{-0.02}$ s	$0.14^{+0.04}_{-0.03}$ s
114	285	171	10.56 ± 0.05	$0.15^{+0.14}_{-0.05}$ s	$0.04^{+0.01}_{-0.01}$ s
113	286	173	9.79 ± 0.05	$9.5^{+6.3}_{-2.7}$ s	$2.5^{+1.1}_{-0.7}$ s
113	285	172	10.01 ± 0.04	$4.2^{+1.4}_{-0.8}$ s	$0.6^{+0.19}_{-0.14}$ s
113	284	171	10.12 ± 0.01	$0.97^{+0.12}_{-0.10}$ s	$0.31^{+0.02}_{-0.02}$ s
113	283	170	10.38 ± 0.01	75^{+136}_{-30} ms	$61^{+3.6}_{-4.0}$ ms
113	282	169	10.78 ± 0.08	73^{+134}_{-29} ms	$5.6^{+3.4}_{-2.1}$ ms
112	285	173	9.32 ± 0.02	28^{+9}_{-6} s	32^{+5}_{-4} s
112	283	171	9.66 ± 0.02	$4.2^{+1.1}_{-0.7}$ s	$3.1^{+0.4}_{-0.4}$ s
112	281	169	10.45 ± 0.04	$0.13^{+0.12}_{-0.04}$ s	$0.02^{+0.005}_{-0.005}$ s
111	282	171	9.16 ± 0.03	100^{+70}_{-30} s	49^{+13}_{-9} s
111	281	170	9.41 ± 0.05	17^{+6}_{-3} s	$8^{+3.9}_{-2.2}$ s
111	280	169	10.15 ± 0.01	$4.2^{+0.6}_{-0.4}$ s	$0.06^{+0.003}_{-0.004}$ s
111	279	168	10.53 ± 0.16	90^{+170}_{-40} ms	$5.9^{+9.7}_{-3.6}$ ms
111	278	167	10.85 ± 0.08	$4.2^{+7.5}_{-1.7}$ ms	$0.94^{+14.03}_{-0.34}$ ms
110	281	171	8.85 ± 0.03	$12.7^{+4.0}_{-2.5}$ s	227^{+60}_{-47} s
110	279	169	9.85 ± 0.02	$0.21^{+0.04}_{-0.04}$ s	$0.19^{+0.03}_{-0.02}$ s
110	277	167	10.71 ± 0.04	$4.1^{+3.7}_{-1.3}$ ms	$1.0^{+0.29}_{-0.20}$ ms
109	278	169	9.58 ± 0.03	$4.5^{+3.5}_{-1.3}$ s	$0.53^{+0.12}_{-0.10}$ s
109	276	167	10.10 ± 0.01	$0.52^{+0.10}_{-0.10}$ s	$0.02^{+0.001}_{-0.001}$ s
109	275	166	10.48 ± 0.01	20^{+24}_{-7} ms	$1.9^{+0.18}_{-0.11}$ ms
108	275	167	9.45 ± 0.02	$0.20^{+0.18}_{-0.06}$ s	$0.63^{+0.09}_{-0.08}$ s
108	273	165	9.67 ± 0.04	$0.76^{+0.71}_{-0.24}$ s	$0.15^{+0.05}_{-0.03}$ s
107	274	167	8.94 ± 0.03	44^{+34}_{-13} s	$10^{+3.4}_{-1.4}$ s
107	272	165	9.21 ± 0.01	$10.6^{+1.6}_{-1.1}$ s	$1.6^{+0.15}_{-0.10}$ s
107	271	164	9.42 ± 0.07	$1.5^{+2.8}_{-0.6}$ s	$0.39^{+0.24}_{-0.15}$ s
107	270	163	9.06 ± 0.08	61^{+292}_{-28} s	$5.2^{+4.2}_{-2.2}$ s
106	271	165	8.67 ± 0.08	$1.6^{+1.5}_{-0.5}$ min	$0.65^{+0.56}_{-0.30}$ min
106	269	163	8.63 ± 0.06	$3.1^{+3.7}_{-1.1}$ min	$0.95^{+0.58}_{-0.35}$ min

TABLE III. Predictions on α half-lives of superheavy nuclei that are not yet synthesized.

Z	A	N	Q Value (MeV)	$\log_{10}[T_{1/2}(\text{s})]$
106	257	151	9.655	−1.207
106	268	162	8.140	3.513
107	262	155	10.311	−2.726
107	263	156	10.256	−2.601
108	261	153	10.935	−3.924
108	262	154	10.987	−4.066
109	266	157	11.311	−4.566
109	267	158	11.077	−4.040
110	265	155	12.290	−6.343
110	266	156	12.187	−6.150
111	272	161	11.274	−3.943
111	274	163	11.299	−4.036
112	271	159	12.310	−5.885
112	279	167	11.435	−4.117
113	279	166	12.150	−5.386
113	281	168	11.300	−3.515
114	283	169	10.896	−2.232
114	284	170	10.592	−1.461
115	286	171	10.552	−1.050
115	292	177	9.960	0.514
116	287	171	11.306	−2.665
116	288	172	11.314	−2.702
117	290	173	11.865	−3.716
117	292	175	11.780	−3.555
118	291	173	12.447	−4.708
118	292	174	12.268	−4.339
119	296	177	12.505	−4.615
119	297	178	12.455	−4.525
120	295	175	13.303	−5.933
120	300	180	13.351	−6.109
121	304	183	13.313	−5.815
121	306	185	13.846	−6.861
122	301	179	14.292	−7.314
122	306	184	13.839	−6.572
123	310	187	14.540	−7.624
123	312	189	12.932	−4.596
124	307	183	14.715	−7.614
124	312	188	13.894	−6.218
125	316	191	13.761	−5.751
125	318	193	13.374	−5.021
126	313	187	15.406	−8.344
126	320	194	13.229	−4.471
127	320	193	13.796	−5.325
127	322	195	13.238	−4.234
128	319	191	14.590	−6.523
128	320	192	14.312	−6.031
129	326	197	14.051	−5.360
129	327	198	14.091	−5.452
130	324	194	14.488	−5.880
130	325	195	14.362	−5.661
131	334	203	13.880	−4.597
131	336	205	13.702	−4.270
132	331	199	15.252	−6.827
132	332	200	15.082	−6.546
133	329	196	10.046	6.068
133	330	197	10.253	5.361
134	333	199	10.591	4.578
134	334	200	10.498	4.855

present approach is found to be 0.34, whereas while using the GLDM of Royer, the standard deviation is 0.56.

Since we obtained a better matching with the experimental results, we have predicted the half-lives of all the experimentally synthesized superheavy nuclei using the present method. Table II gives the comparison of predicted half-lives of superheavy nuclei with experimental results. The experimental Q values and half-lives are taken from Oganessian *et al.* [31]. The matching between experimental and theoretical results suggest the applicability of GLDM with the proximity potential of Blocki *et al.* [24] in predicting the α-decay half-lives of superheavy nuclei. In the present work we would like to mention that all the calculations have been performed without considering the rotational contribution.

As we are successful in reproducing the α half-lives of experimentally synthesized superheavy nuclei, we extended our calculations to predict the half-lives of some unknown isotopes in superheavy region. These predictions are given in Table III. The Q values given in column 4 are calculated using the equation

$$Q = \Delta M_p - (\Delta M_\alpha + \Delta M_d) + k\big(Z_p^\varepsilon - Z_d^\varepsilon\big). \qquad (16)$$

Here ΔM_p, ΔM_d, and ΔM_α represent the mass excess of the parent, daughter, and the α particle, respectively. The electron screening effect on the energy of α particle is included by adding the term $k(Z_p^\varepsilon - Z_d^\varepsilon)$ in Eq. (16). The term kZ^ε is the total binding energy of Z electrons in the atom. Here $k = 8.7$ eV and $\varepsilon = 2.517$ for nuclei with $Z \geqslant 60$ and $k = 13.6$ eV and $\varepsilon = 2.408$ for nuclei with $Z < 60$ [32,33]. The mass excess values of the nuclei are taken from the WS4 mass table [34]. Recently, Wang *et al.* [35] have studied the α-decay half-lives of SHN with $Z \geqslant 100$ using 20 mass models and 18 empirical formulas and found that the WS4 mass model [34] is the most accurate one to reproduce the experimental Q values.

Since the α half-lives of all these isotopes are within the experimental limits, these isotopes may be predicted to be detected in laboratories via α-decay.

IV. CONCLUSIONS

The GLDM proposed by Royer *et al.* have been modified by incorporating the proximity potential proposed by Blocki *et al.* The α-decay half-lives of all the experimentally identified superheavy nuclei are evaluated with the present formalism. The results are compared with the experimental half-lives and half-lives proposed by Royer. Predictions on half-lives are also performed for some of the isotopes of superheavy nuclei, which are not synthesized yet. We hope that our predictions on the α half-lives of superheavy nuclei will be helpful in future experimental investigations in this field.

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