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Theoretical and experimental α decay half-lives of the heaviest odd-Z elements and general predictions

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Theoretical α decay half-lives of the heaviest odd-Z nuclei are calculated using the experimental Q_α value. The barriers in the quasimolecular shape path are determined within a Generalized Liquid Drop Model (GLDM) and the WKB approximation is used. The results are compared with calculations using the Density-Dependent M3Y (DDM3Y) effective interaction and the Viola-Seaborg-Sobiczewski (VSS) formulas. The calculations provide consistent estimates for the half-lives of the α decay chains of these superheavy elements. The experimental data stand between the GLDM calculations and VSS ones in the most time. Predictions are provided for the α decay half-lives of other superheavy nuclei within the GLDM and VSS approaches using the recent extrapolated Q_α of Audi, Wapstra, and Thibault [Nucl. Phys. **A729**, 337 (2003)], which may be used for future experimental assignment and identification.

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The possibility of synthesizing superheavy elements by cold or warm fusion reactions [1–3] or by using radioactive ion beams has renewed interest in investigating the fusion barriers. The main observed decay modes of these heaviest systems are α emission and fission and an accurate description of the α decay is required. The pure Coulomb barrier sharply peaked at the touching point alone does not allow us to determine correctly the fusion cross sections and the partial α decay half-lives. In the fusion path, the nucleon-nucleon forces act before the formation of a neck between the two quasispherical colliding ions and a proximity energy term must be added in the usual development of the liquid-drop model [4]. It is highly probable that the α decay takes place also in this fusion-like deformation valley where the one-body shape keeps quasispherical ends while the transition between one- and two-body configurations corresponds to two spherical nuclei in contact. Consequently, the proximity energy term plays also a main role in correctly describing the α decay barrier. The generalized liquid drop model (GLDM), which includes such a proximity energy term, has made it possible to describe the fusion [5], fission [6], light nucleus [7], and α emission [8] processes. The formation and α decay of superheavy elements have been investigated [9] taking into account the experimental Q_α value or the value provided by the Thomas-Fermi model [10]. The heaviest even-Z nuclei have been studied [11] using the Q_α value obtained experimentally or given by the FRDM (Finite Range Droplet Model) [12].

Recently, isotopes of the element 115 have been synthesized [13] and observed via the α emission. These new experimental observations of $Z = 115$ have already attracted a lot of theoretical studies [14–21]. Most of the earlier investigations have been devoted to the description of the ground-state properties of superheavy nuclei; we focus on calculating their half-lives following the first work for even-Z nuclei [11]. In Ref. [21], the α decay half-lives of $Z = 115$ isotopes are calculated with the microscopic Density-Dependent M3Y (DDM3Y) interaction, and the results are consistent with the experimental data. The purpose of this work is to determine the partial α decay half-lives of these superheavy elements within the macroscopic GLDM from the experimental Q_α values using the WKB approximation and to compare with the experimental data and the calculations of DDM3Y effective interaction [21] and the Viola-Seaborg formulas with Sobiczewski constants (VSS) [22]. Finally predictions within the GLDM and VSS formulas are given for the partial α decay half-lives of the superheavy nuclei using the recent Q_α decay energies of Audi, Wapstra, and Thibault [23].

The GLDM energy is widely explained in Ref. [11] and not recalled here. The half-life of the parent nucleus decaying via α emission is calculated using the WKB barrier penetration probability. In such a unified fission model, the decay constant of the α emitter is simply defined as $\lambda = \nu_0 P$, where the assault frequency ν_0 has been taken as $\nu_0 = 10^{19} s^{-1}$, P being the barrier penetrability.

The α decay half-lives of the recently produced odd-Z superheavy nuclei calculated with the three approaches and using the experimental Q_α values and without considering the rotational contribution are presented in Table I. The Q_α values given in Ref. [23] are obtained by extrapolation. Within the GLDM the quantitative agreement with experimental data is visible. The experimental half-lives are reproduced well in six ($^{288}115$, $^{284}113$, $^{272}107$, $^{287}115$, $^{283}113$, $^{275}109$) of nine nuclei along the decay chains of $^{288}115$ and $^{287}115$. Two results ($^{280}111$, $^{276}109$) are underestimated about four to five times, possibly because the centrifugal barrier required for the spin-parity conservation could not be taken into account because of the nonavailability of the spin-parities of the decay chain nuclei. On the whole, the results agree well with the experimental data, indicating that a GLDM taking into account the proximity effects and the mass asymmetry is sufficient to reproduce the α decay potential barriers when the experimental Q_α value is known. The results obtained with the DDM3Y interaction agree with the experimental data as well as the GLDM predictions and largely better

TABLE I. Comparison between experimental α decay half-lives [13] and results obtained with the GLDM, the DDM3Y effective interaction [21], and the VSS formulas.

Parent Nuclei	Exp. Q (MeV)	[23] Q (MeV)	Exp. $T_{1/2}$	DDM3Y $T_{1/2}(Q_{\mathrm{ex}})$	GLDM $T_{1/2}(Q_{\mathrm{ex}})$	GLDM $T_{1/2}(Q_{\mathrm{Audi}})$	VSS $T_{1/2}(Q_{\mathrm{ex}})$	VSS $T_{1/2}(Q_{\mathrm{Audi}})$
$^{288}115$	10.61(6)		87^{+105}_{-30} ms	409 ms	$94.7^{+41.9}_{-28.9}$ ms		997^{+442}_{-303} ms	
$^{284}113$	10.15(6)	10.25	$0.48^{+0.58}_{-0.17}$ s	$1.55^{+0.72}_{-0.48}$s	$0.43^{+0.21}_{-0.13}$ s	0.23 s	$4.13^{+1.94}_{-1.31}$ s	2.19s
$^{280}111$	9.87(6)	9.98	$3.6^{+4.3}_{-1.3}$ s	$1.9^{+0.9}_{-0.6}$ s	$0.69^{+0.33}_{-0.23}$ s	0.34 s	$5.70^{+2.74}_{-1.84}$ s	2.79s
$^{276}109$	9.85(6)	9.80	$0.72^{+0.87}_{-0.25}$ s	$0.45^{+0.23}_{-0.14}$s	$0.19^{+0.08}_{-0.06}$ s	0.26 s	$1.44^{+0.68}_{-0.46}$ s	1.99s
$^{272}107$	9.15(6)	9.30	$9.8^{+11.7}_{-3.5}$ s	$10.1^{+5.4}_{-3.4}$ s	$5.12^{+3.19}_{-1.58}$ s	1.89 s	$33.8^{+17.9}_{-11.6}$ s	11.91s
$^{287}115$	10.74 (9)		32^{+155}_{-14} ms	49 ms	$46.0^{+33.1}_{-19.1}$ ms		207^{+149}_{-85} ms	
$^{283}113$	10.26 (9)	10.60	100^{+490}_{-45} ms	$201.6^{+164.9}_{-84.7}$ms	222^{+172}_{-96} ms	27.1 ms	937^{+719}_{-402} s	116.7ms
$^{279}111$	10.52(16)	10.45	170^{+810}_{-80} ms	$9.6^{+14.8}_{-5.7}$ ms	$12.4^{+19.9}_{-7.6}$ ms	18.8 ms	$45.3^{+73.1}_{-27.6}$ ms	68.8ms
$^{275}109$	10.48 (9)	10.12	$9.7^{+46}_{-4.4}$ ms	$2.75^{+1.85}_{-1.09}$ms	$4.0^{+2.8}_{-1.6}$ ms	35.2 ms	$13.7^{+9.6}_{-5.6}$ ms	119.5ms

than the VSS calculations. This shows that a double folding potential obtained using the M3Y [24] effective interaction supplemented by a zero-range potential for the single-nucleon exchange is very appropriate because its microscopic nature includes many nuclear features, in particular, a potential energy surface is inherently embedded in this description. This double agreement shows that the experimental data themselves seem to be consistent. For most nuclei the predictions of the VSS model largely overestimate the half-lives. The blocking effect is probably treated too roughly.

One can also find that all calculated half-lives of the $^{279}111$ nucleus are smaller than the experimental ones in Table I. The introduction of the centrifugal barrier would allow to improve the agreement between the theoretical and experimental data.

The experimental α decay half-lives are between the close theoretical values given by the GLDM and the ones derived from the VSS formulas. Thus predictions of the α decay half-lives with the GLDM and VSS formulas are possible as long as we know the right α decay energies. The ones derived from Audi, Wapstra, and Thibault's recent publication [23] are very close to the experimental data. The greatest deviation is not more than 0.5 MeV, which is a valuable result for studying correctly the half-lives. The calculations using the α decay energies of Ref. [23] for the nuclei of the $^{288}115$ and $^{287}115$ decay chains by the GLDM and VSS formulas are reasonably consistent with the experimental data. The experimental data stand between the calculations of the GLDM and the results of VSS in six of the seven nuclei when experimental uncertainty in the Q value is considered. Thus, predictions of the half-lives of superheavy nuclei from the GLDM and VSS formulas are provided for a large number of superheavy elements in Table II using the extrapolated Q_α values given by Ref. [23] or the experimental data indicated by an asterisk. They are an improvement relative to the values previously given in Ref. [9]

TABLE II. Predicted α decay half-lives using the GLDM and the VSS formulas. The α decay energies are taken from the extrapolated data of Audi, Wapstra, and Thibault [23] or the experimental data indicated by an asterisk.

Nuclei	Q (MeV)	$T_{1/2}^{\mathrm{GLDM}}$	$T_{1/2}^{\mathrm{VSS}}$	Nuclei	Q (MeV)	$T_{1/2}^{\mathrm{GLDM}}$	$T_{1/2}^{\mathrm{VSS}}$	Nuclei	Q (MeV)	$T_{1/2}^{\mathrm{GLDM}}$	$T_{1/2}^{\mathrm{VSS}}$
$^{293}118$	12.30	77 μs	592 μs	$^{292}117$	11.60	1.30 ms	13.33 ms	$^{292}116$	10.71	94.6 ms	84.7 ms
$^{291}117$	11.90	0.29 ms	1.23 ms	$^{291}116$	11.00	17.7 ms	176 ms	$^{291}115$	10.00	4.33 s	21.9 s
$^{290}116$	11.30	3.36 ms	2.75 ms	$^{290}115$	10.30	0.62 s	6.86 s	$^{289}116$	11.70	0.43 ms	3.63 ms
$^{289}115$	10.60	97.4 ms	482 ms	$^{289}114$	9.85	5.81 s	55.72 s	$^{288}115$	11.00	9.41 ms	99.1 ms
$^{288}114$	9.97	2.67 s	2.15 s	$^{287}115$	11.30	1.92 ms	8.29 ms	$^{287}114$	10.44	0.136 s	1.24 s
$^{287}113$	9.34	102 s	461 s	$^{286}114$	10.70	30 ms	22 ms	$^{286}113$	9.68	9.44 s	92.5 s
$^{285}114$	11.00	5.1 ms	44.6 ms	$^{285}113$	10.02	0.99 s	4.35 s	$^{285}112$	8.79	49.97 min	425 min
$^{284}113$	10.25	0.23 s	2.19 s	$^{284}112$	9.30	64.7 s	47.3 s	$^{283}113$	10.60	27.1 ms	116.7ms
$^{283}112$	9.62	6.93 s	58.09 s	$^{283}111$	8.96	6.01 min	25.73 min	$^{282}112$	9.96	0.772 s	0.516 s
$^{282}111$	9.38	18.6 s	158.4 s	$^{281}112$	10.28	0.102 s	0.786 s	$^{281}111$	9.64	3.12 s	11.96 s
$^{281}110$	8.96	3.05 min	22.47 min	$^{280}112$	10.62	13.3 ms	8.62 ms	$^{280}111$	9.98	0.335 s	2.79 s
$^{280}110$	9.30	15.5 s	9.76 s	$^{279}112$	10.96	2.06 ms	14.1 ms	$^{279}111$	10.45	18.8 ms	68.8 ms
$^{279}110$	9.60	2.02 s	14.3 s	$^{279}109$	8.70	10.35 min	36.32 min	$^{278}112$	11.38	0.223 ms	0.121ms
$^{278}111$	10.72	3.89 ms	30.9 ms	$^{278}110$	10.00	148.5 ms	89.8 ms	$^{278}109$	9.10	31 s	240 s
$^{277}112$	11.62	0.069 ms	0.402 ms	$^{277}111$	11.18	0.323 ms	1.073 ms	$^{277}110$	10.30	23.1 ms	162 ms
$^{277}109$	9.50	1.89 s	6.61 s	$^{277}108$	8.40	49.7 min	330.3 min	$^{276}111$	11.32	0.157 ms	1.11 ms
$^{276}110$	10.60	4.03 ms	2.35 ms	$^{276}109$	9.80	0.26 s	1.99 s	$^{276}108$	8.80	131 s	75 s

TABLE II. (*Continued.*)

Nuclei	Q (MeV)	$T_{1/2}^{\mathrm{GLDM}}$	$T_{1/2}^{\mathrm{VSS}}$	Nuclei	Q (MeV)	$T_{1/2}^{\mathrm{GLDM}}$	$T_{1/2}^{\mathrm{VSS}}$	Nuclei	Q (MeV)	$T_{1/2}^{\mathrm{GLDM}}$	$T_{1/2}^{\mathrm{VSS}}$
$^{275}111$	11.55	51.5 μs	152 μs	$^{275}110$	11.10	0.26 ms	1.65 ms	$^{275}109$	10.12	35.2 ms	119.5 ms
$^{275}108$	9.20	7.13 s	47.2 s	$^{274}111$	11.60	41.4 μs	258 μs	$^{274}110$	11.40	55.5 μs	28.7 μs
$^{274}109$	10.50	3.67 ms	26.8 ms	$^{274}108$	9.50	0.92 s	0.51 s	$^{274}107$	8.50	9.94 min	70.98 min
$^{273}111$	11.20	0.33 ms	0.96 ms	$^{273}110$	11.37	0.067 ms	0.39 ms	$^{273}109$	10.82	0.61 ms	1.96 ms
$^{273}108$	9.90	69.4 ms	441.6 ms	$^{273}107$	8.90	28.8 s	92.8 s	$^{272}111$	11.44	0.11 ms	0.59 ms
$^{272}110$	10.76	1.97 ms	0.94 ms	$^{272}109$	10.60	2.34 ms	15.02 ms	$^{272}108$	10.10	21.7 ms	10.9 ms
$^{272}107$	9.30	1.89 s	11.91 s	$^{272}106$	8.30	24.9 min	11.4 min	$^{271}110$	10.87	1.12 ms	5.86 ms
$^{271}109$	10.14	37.5ms	105.6 ms	$^{271}108$	9.90	79.2 ms	441.7 ms	$^{271}107$	9.50	0.499 s	1.40 s
$^{271}106$	9.20	1.74 s	16.78 s	$^{270}110$	11.20	0.199 ms	0.083 ms	$^{270}109$	10.35	10.7 ms	65 ms
$^{270}108$	9.30	4.48 s	2.02 s	$^{270}107$	9.30	2.0 s	11.9 s	$^{270}106$	9.10	3.59 s	1.66 s
$^{270}105$	8.20	24.38 min	140.53 min	$^{269}110$	11.58	30 μs	132μs	$^{269}109$	10.53	3.75 ms	10.25 ms
$^{269}108$	9.63	0.48 s	2.52 s	$^{269}107$	8.84	55.9 s	144.5 s	$^{269}106$	8.80	32.5 s	167.9 s
$^{269}105$	8.40	4.96 min	12.93 min	$^{268}110$	11.92	6.3 μs	2.1μs	$^{268}109$	10.73	1.28 ms	7.15 ms
$^{268}108$	9.90	85.7 ms	37.7 ms	$^{268}107$	9.08	9.86 s	55.5 s	$^{268}106$	8.40	12.1 min	5.1 min
$^{268}105$	8.20	25.4 min	140.5 min	$^{268}104$	8.10	23.8 min	10.2 m	$^{267}110$	12.28	1.3 μs	4. 4μs
$^{267}109$	10.87	0.61 ms	1.49 ms	$^{267}108$	10.12	22.1 ms	112.5 ms	$^{267}107$	9.37	1.33 s	3.36 s
$^{267}106$	8.64	1.9 min	9.3 min	$^{267}105$	7.90	330 min	787 min	$^{267}104$	7.80	315 min	1494 min
$^{266}109$	10.996	0.32 ms	1.63 ms	$^{266}108$	10.336	6.26 ms	2.64 ms	$^{266}107$	9.55	0.41 s	2.21 s
$^{266}106$	8.88	19.3 s	8.02 s	$^{266}105$	8.19	29.0 min	152.5 min	$^{266}104$	7.50	81.47 h	31.30 h
$^{265}109$	11.07	0.223 ms	0.498 ms	$^{265}108$	10.59	1.47 ms	7.00 ms	$^{265}107$	9.77	99.7 ms	241 ms
$^{265}106$	9.08*	4.7 s	22.2 s	$^{265}105$	8.49	2.70 min	6.43 min	$^{265}104$	7.78	6.58 h	29.65 h
$^{264}108$	10.59*	1.58 ms	0.60 ms	$^{264}107$	9.97	29.9 ms	151 ms	$^{264}106$	9.21	1.99 s	0.77 s
$^{264}105$	8.66	46.1 s	232 s	$^{264}104$	8.14	19.2 min	7.36 min	$^{263}108$	10.67	1.03 ms	4.45 ms
$^{263}107$	10.08	15.5 ms	34.9 ms	$^{263}106$	9.39	0.60 s	2.64 s	$^{263}105$	9.01	3.65 s	8.27 s
$^{263}104$	8.49	72.7 s	324.7 s	$^{262}107$	10.30	4.42 ms	20.5 ms	$^{262}106$	9.60	160.4 ms	56.7 ms
$^{262}105$	9.01	4.06 s	18.2 s	$^{262}104$	8.49	82.6 s	27.9 s	$^{261}107$	10.56	1.04 ms	2.07 ms
$^{261}106$	9.80	44.8 ms	183.9 ms	$^{261}105$	9.22	0.96 s	1.92 s	$^{261}104$	8.65*	25.0 s	97.2 s
$^{260}107$	10.47	1.77 ms	7.62 ms	$^{260}106$	9.92*	21.9 ms	7.48 ms	$^{260}105$	9.38	0.33 s	1.44 s
$^{260}104$	8.90	4.09 s	1.35 s	$^{259}106$	9.83	39.4 ms	152.3 ms	$^{259}105$	9.62	69.0 ms	136.7 ms
$^{259}104$	9.12	0.89 s	3.38 s	$^{258}106$	9.67	114 ms	36 ms	$^{258}105$	9.48	0.18 s	0.74 ms
$^{258}104$	9.25	380 ms	120 ms	$^{257}105$	9.23	1.0 s	1.8 s	$^{257}104$	9.04	1.66 s	5.88 s
$^{256}105$	9.46	230 ms	848 ms	$^{256}104$	8.93*	3.78 s	1.09 s	$^{255}105$	9.72	42.9 ms	72.4 ms
$^{255}104$	9.058	1.57 s	5.19 s	$^{254}104$	9.38	181 ms	50.5 ms	$^{253}104$	9.55	63.1 ms	195.0 ms

because these extrapolated Q_α values are in better agreement with the experimental data than the ones proposed in Ref. [10]. This may be useful for future experimental assignment and identification.

In conclusion, the half-lives for α radioactivity have been analyzed in the quasimolecular shape path within a GLDM including the proximity effects between nucleons and the mass and charge asymmetry. The results are in agreement with the experimental data for the α decay half-lives along the decay chains of the $Z = 115$ isotopes and close to the ones derived from the DDM3Y effective interaction. The experimental α decay half-lives stand between the GLDM calculations and the VSS formula results and the α decay half-lives of some superheavy nuclei have been presented within the GLDM and VSS approaches and Q_α adopted from Audi, Wapstra, and Thibault's [23] recent extrapolated data.

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[1] S. Hofmann and G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
[2] P. Armbruster, Eur. Phys. J. A **7**, 23 (2000).
[3] Yu. Ts. Oganessian *et al.*, Phys. Rev. Lett. **83**, 3154 (1999); Eur. Phys. J. A **5**, 63 (1999); Nature **400**, 242 (1999).
[4] J. Blocki, J. Randrup, W. J. Swiatecki, and C. F. Tsang, Ann. Phys. **105**, 427 (1977).
[5] G. Royer and B. Remaud, Nucl. Phys. **A444**, 477 (1985).
[6] G. Royer and K. Zbiri, Nucl. Phys. **A697**, 630 (2002).
[7] G. Royer and R. Moustabchir, Nucl. Phys. **A683**, 182 (2001).

[8] G. Royer, J. Phys. G: Nucl. Part. Phys. **26**, 1149 (2000).
[9] G. Royer and R. A. Gherghescu, Nucl. Phys. **A699**, 479 (2002).
[10] W. D. Myers and W. J. Swiatecki, Nucl. Phys. **A601**, 141 (1996).
[11] H. F. Zhang, W. Zuo, J. Q. Li, and G. Royer, Phys. Rev. C **74**, 017304 (2006).
[12] P. Möller, J. R. Nix, and K.-L. Kratz, At. Data Nucl. Data Tables **66**, 131 (1997).
[13] Yu. Ts. Oganessian, V. K. Utyonkoy, Yu. V. Lobanov *et al.*, Phys. Rev. C **69**, 021601(R) (2004); **69**, 029902(E) (2004); Yu. Ts. Oganessian, V. K. Utyonkoy, S. N. Dmitriev *et al.*, Phys. Rev. C **72**, 034611 (2005).
[14] Zhongzhou Ren, Ding-Han Chen, Fei Tai, H. Y. Zhang, and W. Q. Shen, Phys. Rev. C **67**, 064302 (2003).
[15] L. S. Geng, H. Toki, and J. Meng, Phys. Rev. C **68**, 061303(R) (2003).
[16] Sankha Das and G. Gangopadhyay, J. Phys. G: Nucl. Part. Phys. **30**, 957 (2004).
[17] M. M. Sharma, A. R. Farhan, and G. Münzenberg, Phys. Rev. C **71**, 054310 (2005).
[18] Y. K. Gambhir, A. Bhagwat, and M. Gupta, Ann. Phys. **320**, 429 (2005).
[19] H. Zhang, J. Li, W. Zuo, Z. Ma, B. Chen, and S. Im, Phys. Rev. C **71**, 054312 (2005).
[20] E. Baldini-Neto, B. V. Carlson, and D. Hirata, J. Phys. G: Nucl. Part. Phys. **32**, 655 (2006).
[21] D. N. Basu, J. Phys. G: Nucl. Part. Phys. **30**, B35 (2004); P. Roy Chowdhury, D. N. Basu, and C. Samanta, Phys. Rev. C **75**, 047306 (2007).
[22] V. E. Viola and G. T. Seaborg, J. Inorg. Nucl. Chem. **28**, 741 (1966); A. Sobiczewski, Z. Patyk, and S. Cwiok, Phys. Lett. **B224**, 1 (1989).
[23] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003).
[24] G. Bertsch, J. Borysowicz, H. McManus, and W. G. Love, Nucl. Phys. **A284**, 399 (1977).