Systematic calculations of α decay properties based on results from recent experiments

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(Received 5 August 2013; revised manuscript received 18 September 2013; published 25 October 2013)

We have performed a systematical investigation on the new or improved data of α decay in recent experiments, including neutron-deficient nuclei around the proton drip line and superheavy nuclei. By using the double-folding integral of the effective nucleon-nucleon interaction plus the density distributions of the α particle and the daughter nucleus, the deformed α-core potential is constructed. The α decay half-lives are then obtained within the modified two-potential approach. These obtained α decay half-lives are found to be in good agreement with the corresponding experimental data. This shows that the present model and formulas of α decay are valid for some new mass ranges.

DOI: 10.1103/PhysRevC.88.044329 PACS number(s): 23.60.+e, 21.60.Gx, 21.10.Tg

I. INTRODUCTION

Whatever concerns modern physics or chemistry, α decay plays an important role in the corresponding development. In contemporary nuclear physics, α decay has also been considered as a powerful tool to probe into detailed nuclear structure, especially for nuclei in the vicinity of the proton drip line and in the superheavy mass region, and so on. Recently, a series of experiments were carried out for the detection of α decay properties of very neutron-deficient nuclei close to the proton drip line [1–7]. Considerable data on α emissions of these studied isotopes have been acquired for the first time or with improved accuracy, usually involving valuable structural information. The measurements on α decay chains originating from the $\pi s_{1/2}$ and $\pi h_{11/2}$ states in ^{173}Au were used to pursue information on the nuclear mass surface [1]. Besides, α decay branching ratios of ^{178,179}Hg were first deduced with the help of correlated α decay chains [2], and the α decay spectroscopy of ^{179}Tl and its sequential products was studied in two complementary experiments [3]. Special attention was also paid to the decay feature for very proton-rich isotopes of Fr produced in fusion-evaporation reactions [4–6]. Meanwhile, the accumulation of data on most neutron-deficient isotopes in the region from Pb to Th provides an excellent opportunity to validate the effect of shell closure $Z = 82$ and $N = 126$ in the α decay process [7]. On the other hand, α decay chains are crucial in the identification and recognition of new superheavy elements or isotopes. After the new element 117 was discovered in the hot fusion procedure [8], further experiments have been performed to explore the daughter product and decay properties of the isotopes of element 117 [9–11]. Moreover, it is impressive to note that the partial α decay half-life and the α decay energy of the deformed doubly magic nucleus ^{270}Hs were simultaneously measured for the first time within the ^{226}Ra + ^{48}Ca reaction [12]. Besides, there are also other new results owing to the rapid development of experimental facilities and technology [13–15], such as investigations on the heaviest isotopes with $Z = 113$, 114 [13,14], and even an isomeric state in ^{261}Rf [15].

Theoretically, various models have been proposed to give the quantitative description of α decay and heavier cluster emission [16–30]. Strikingly, the above-mentioned experiments not only extend the research field but also in fact result in a close examination of theoretical models. It is of physical significance to interpret new or improved α decay data, especially for these exotic nuclei around the proton drip line and the newly produced superheavy nuclei. Not long ago, we combined the modified two-potential approach (MTPA) for deformed nuclei with the density-dependent cluster model to straightforwardly evaluate the α decay half-lives [31,32]. The reasonable agreement between theory and experiment is achieved in this framework for a large range of nuclei, even including the exotic α emitters around the $N = 126$ neutron shell [31] and the unfavored α decays from ground states to ground states in the range $53 \leqslant Z \leqslant 91$ [32]. As a further test, we extend our previous studies to the detailed calculation of these new or improved α decay data in this work. Additionally, the phenomenological curve of α decay half-lives is employed for comparison as well.

In the following, we initially give a brief introduction to the present theoretical framework of the α decay half-life calculation in Sec. II. Section III represents the comparison of the calculated results with the recent experimental data. A summary is given in Sec. IV.

II. THEORETICAL FRAMEWORK

Based on the assumption that an α particle interacts with an axially symmetric deformed core nucleus, the total interaction potential of the α-core system, comprising the nuclear and Coulomb potentials plus the centrifugal part, is given as

$$V(r,\theta) = \lambda V_N(r,\theta) + V_C(r,\theta) + \frac{\hbar^2 \ell(\ell+1)}{2\mu r^2}, \qquad (1)$$

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where λ is the depth of nuclear potential, θ is the orientational angle of the emitted α particle with respect to the symmetric axis of the daughter nucleus, μ is the reduced mass of the α-core system, and ℓ is the angular momentum carried by the emitted particle. The nuclear and Coulomb potentials are microscopically established via the double-folding integral

$$V_{NorC}(\mathbf{r},\theta) = \iint d\mathbf{r_1}d\mathbf{r_2}\rho_1(\mathbf{r_1})\upsilon(\mathbf{s} = |\mathbf{r_2}+\mathbf{r}-\mathbf{r_1}|)\rho_2(\mathbf{r_2}), \tag{2}$$

where $\upsilon(\mathbf{s})$ represents the effective M3Y nucleon-nucleon interaction and the standard Coulomb proton-proton interaction, respectively, for the nuclear potential and the Coulomb one. Different from the Gaussian density distribution ρ_1 of the spherical α cluster, the density distribution ρ_2 of the daughter nucleus is supposed to be in a deformed Fermi behavior,

$$\rho_2(r_2,\theta) = \frac{\rho_0}{1+\exp\left[\frac{r_2-R(\theta)}{a}\right]}. \tag{3}$$

Here $R(\theta) = R_0[1+\beta_2 Y_{20}(\theta)+\beta_4 Y_{40}(\theta)]$, and the half-density radius and diffuseness parameters are fixed as $R_0 = 1.07\ A_d^{1/3}$ fm and a = 0.54 fm (see Refs. [20,31,33] and references therein for details of the double-folding procedure). The ρ_0 value is determined by integrating the density distribution equivalent to the mass or atomic number of the corresponding daughter nucleus for the nuclear and Coulomb potentials, respectively. The quadrupole and hexadecapole deformation parameters of the residual daughter nucleus, i.e., β_2 and β_4, are chosen as the evaluated values obtained by Möller *et al*. [34]. The total potential $V(r,\theta)$ can be then reduced into a one-dimensional case for one certain orientation angle θ, namely $V(r)$. Subsequently, one can obtain the α decay width $\Gamma(\theta)$ for the given angle following the two-potential approach for deformed nuclei, as described in previous studies [31,32]. By a careful averaging of $\Gamma(\theta)$ in all directions [20,25,35], the final decay width is ultimately given by

$$\Gamma = \int_0^{\pi/2} \Gamma(\theta)\sin(\theta)d\theta. \tag{4}$$

Then the half-life of α decay is related as

$$T_{1/2} = \frac{\hbar \ln 2}{P_\alpha \Gamma}, \tag{5}$$

where the indispensable quantity P_α, depicting the preformation probability of an α particle in the parent nucleus, is taken as the same constant for one kind of nuclei [17,20]. In detail, we directly make use of previous choices without modifications, i.e., $P_\alpha^{e\text{-}e} = 0.38$ $P_\alpha^{odd\text{-}A} = 0.27$ and $P_\alpha^{o-o} = 0.17$. These values are consistent with other α decay studies [17,20,35] and the microscopic calculation of the typical nucleus ^{212}Po [16]. It should be better that the preformation factor is regarded as a variable dependent upon different parent nuclei instead of a constant, and this is worth further investigation. As mentioned before, we also perform a comparison of the present results with the estimated values in the empirical relation. In the previous work of our group, there is an interesting attempt to pursue a unified description (UD) on half-lives of both α decay and cluster radioactivity [36],

$$\log_{10} T_{1/2} = 0.39961\sqrt{\mu}Z_cZ_dQ^{-1/2} - 1.31008\sqrt{\mu}(Z_cZ_d)^{1/2} + a, \tag{6}$$

TABLE I. Comparison of calculated α decay half-lives with the new experimental data for neutron-deficient nuclei. For ^{171}Ir and ^{178,179}Hg, the experimental data are from a combination of the recent measurements [2,3] and previous works [38,39]. The superscripts m and n denote the isomeric state.

Transition	$I_i^\pi \to I_j^\pi$	Q_α (MeV)	$T_\alpha^{\rm expt}$	$T_\alpha^{\rm calc}$	$T_\alpha^{\rm UD}$
^{203}Fr$^m \to ^{199}$At^m	$1/2^+ \to 1/2^+$	7.392(5)	228±65 ms [6]	251 ms	178 ms
^{199}Fr$\to ^{195}$At	$1/2^+ \to 1/2^+$	7.821(11)	$4.5^{+3.1}_{-1.3}$ ms [4]	8.6 ms	7.4 ms
^{199}Fr$^m \to ^{195}$At^m	$7/2^- \to 7/2^-$	7.833(6)	$6.2^{+1.1}_{-0.8}$ ms [4]	7.8 ms	6.8 ms
^{198}Fr$^m \to ^{194}$At^m	$2^- \to 2^-$	7.770(15)	15^{+12}_{-5} ms [5]	20 ms	38 ms
^{198}Fr$^n \to ^{194}$At^n	$6^+,7^+ \to 6^+,7^+$	7.842(15)	16^{+13}_{-5} ms [5]	12 ms	23 ms
^{197}Fr$^m \to ^{193}$At^m	$7/2^- \to 7/2^-$	7.888(15)	$0.6^{+3.0}_{-0.3}$ ms [4]	5.5 ms	4.6 ms
^{193}At$^m \to ^{189}$Bi^m	$7/2^- \to 7/2^-$	7.531(30)	30^{+150}_{-10} ms [4]	17 ms	11 ms
^{189}Bi$^n \to ^{185}$Tl^n	$9/2^- \to 9/2^-$	6.809(30)	200^{+980}_{-90} ms [4]	625 ms	490 ms
^{179}Tl$\to ^{175}$Au	$1/2^+ \to 1/2^+$	6.710(4)	443±31 ms [3]	557 ms	170 ms
^{175}Au$\to ^{171}$Ir	$1/2^+ \to 1/2^+$	6.583(4)	232±26 ms [3]	212 ms	74 ms
^{171}Ir$\to ^{167}$Re^m	$1/2^+ \to 1/2^+$	5.871(7)	$21.3^{+16.4}_{-6.6}$ s [3,39]	18.5 s	6.0 s
^{173}Au$\to ^{169}$Ir	$1/2^+ \to 1/2^+$	6.846(14)	28.0±1.3 ms [1]	26.7 ms	8.9 ms
^{173}Au$^m \to ^{169}$Ir^m	$11/2^- \to 11/2^-$	6.899(15)	13.3±0.1 ms [1]	17.5 ms	5.9 ms
^{165}Re$\to ^{161}$Ta	$1/2^+ \to 1/2^+$	5.694(6)	20.6±16.1 s [1]	13.8 s	4.2 s
^{161}Ta$\to ^{157}$Lu	$1/2^+ \to 1/2^+$	5.209(27)		263.3 s	73.5 s
^{161}Ta$^m \to ^{157}$Lu^m	$11/2^- \to 11/2^-$	5.273(6)	87.0±53.0 s [1]	128.5 s	36.9 s
^{178}Hg$\to ^{174}$Pt	$0^+ \to 0^+$	6.577(3)	300.2±16.2 ms [2,38]	417 ms	50.6 ms
^{179}Hg$\to ^{175}$Pt	$7/2^- \to 7/2^-$	6.432(5)	1.41±0.12 s [2,38]	1.91 s	0.98 s

where μ is the reduced mass of the cluster-daughter system measured in the unit of the nucleon mass $\mu = A_c A_d/(A_c + A_d)$, and the subscripts d and c respectively indicate the residual daughter nucleus and the emitted cluster (α particle here). The last a value, similar to the hindrance factor, is taken as follows: $a_{e\text{-}e} = -17.00698$, $a_{e\text{-}o} = -16.26029$, $a_{o\text{-}e} = -16.40484$, and $a_{o\text{-}o} = -15.85337$. The discrepancies between these a values for different kinds of nuclei may be caused by the block effect of valence protons and neutrons.

III. NUMERICAL RESULTS AND DISCUSSIONS

Within the procedures described before, we pay attention to the new or improved α decay data in recent experiments. These α transitions mainly come from two extreme cases, namely the neutron-deficient isotopes around the proton drip line and α emitters in the superheavy mass region. A detailed α decay study was initially performed on the recent data of transitions from ground and isomeric states of isotopes approaching the proton drip line, as demonstrated in Table I. The first column denotes the transition, and the corresponding information on I_i^π and I_j^π is given in the second column. Besides the experimental decay energies and half-lives shown in the next two columns, the calculated half-lives from the MTPA and empirical Eq. (6) are listed in order in the last two columns.

According to these experimental assignments of spin and parity [1–7,37,38], it is believed that these transitions are favored ones (i.e., $\ell = 0$) by picking the smallest value obeying the spin-parity selection rule. No matter whether the parent nucleus is located at the ground state or the low-lying isomeric states, the new experimental α decay half-lives are well reproduced within a mean factor of about 2 in the present framework. Hence the assumption of favored α decays appear to be reasonable. As well, our study is identical with those empirical estimations. With these results in mind, we may conclude that the measured values are somewhat self-consistent, and that the present calculations are suitable for the exotic α emitters near the proton drip line. For a special example, there are actually two possible α decay schemes suggested for ^{199}Fr. However, the given data of an isomeric state are quite close to those among the other scheme involving both the ground and isomeric states of ^{199}Fr, indicating that we should focus on the latter two transitions. Correspondingly, the calculated α decay half-lives are compatible with the newly measured data. Moreover, encouraged by the good agreement between theory and experiment, we have also made a prediction on the unknown half-life of α decay from the ground state of ^{161}Ta.

Table II represents the detailed results for the newly observed α decay of the heaviest nuclei. The experimental data are mainly taken from Refs. [11–13,15,37], including the sequential experiments of element 117 [11], doubly deformed magic nucleus ^{270}Hs [12] and some other interesting isotopes [13,15]. Different from Table I, there is little knowledge of the level scheme in the superheavy mass region. Assuming that the angular momentum carried by the emitted α particle is zero (namely, favored α transitions), the recent α decay data of superheavy nuclei are carefully investigated.

TABLE II. Comparison of α decay half-lives with the measured values in recent experiments [11–13,15,37] for superheavy nuclei. Note that these α transitions are considered favored ones. The asterisk indicates that the corresponding Q_α value is taken by combining the recent measurement [11] and the mass table [37].

Nucleus	Q_α (MeV)	T_α^{expt}	T_α^{calc}	T_α^{UD}
^{270}Hs	9.15(8)	$7.6^{+4.9}_{-2.2}$ s	4.5 s	5.3 s
$^{288}_{114}$Fl	10.09(3)	$0.52^{+0.22}_{-0.13}$ s	1.13 s	1.04 s
$^{289}_{114}$Fl	10.01(3)	$0.97^{+0.97}_{-0.32}$ s	2.62 s	9.83 s
$^{285}_{112}$Cn	9.34(3)	30^{+30}_{-10} s	51 s	188 s
^{282}113	10.78(8)	73^{+134}_{-29} ms	16 ms	108 ms
^{278}Rg	10.85(8)	$4.2^{+7.5}_{-1.7}$ ms	2.1 ms	18.3 ms
^{274}Mt*	10.15(1.12)	$0.44^{+0.81}_{-0.17}$ s	0.03 s	0.25 s
^{270}Bh	9.06(8)	61^{+292}_{-28} s	8 s	62 s
^{287}115	10.74(6)	32^{+58}_{-13} ms	67 ms	163 ms
^{283}113	10.27(9)	100^{+490}_{-45} ms	216 ms	657 ms
^{279}Rg	10.53(16)	$0.17^{+0.81}_{-0.08}$ s	8.01 ms	30.9 ms
^{275}Mt	10.50(6)	12^{+23}_{-5} ms	2 ms	9 ms
^{271}Bh	9.49(16)	$1.2^{+5.9}_{-0.5}$ s	0.3 s	1.0 s
^{288}115	10.48–10.73	171^{+42}_{-28} ms	507–109 ms	2815–618 ms
^{284}113*	10.11(5)	$0.97^{+0.25}_{-0.17}$ s	1.02 s	6.07 s
^{280}Rg	9.22–10.01	$3.6^{+0.9}_{-0.6}$ s	67.0–0.3 s	501.9–2.5 s
^{276}Mt	9.30–10.10	$0.54^{+0.14}_{-0.09}/6^{+8}_{-2}$ s	6.80–0.04 s	57.19–0.34 s
^{272}Bh	8.86–9.29	$12.0^{+3.1}_{-2.1}$ s	33.3–1.6 s	266.5–13.4 s
^{293}117	10.75–11.29	27^{+12}_{-6} ms	268–11 ms	661–28 ms
^{289}115	10.34–10.69	380^{+180}_{-100} ms	715–86 ms	1786–221 ms
^{285}113	9.61–10.32	$5.6^{+2.2}_{-1.2}$ s	18.0–0.2 s	44.4–0.5 s
^{294}117	10.96–11.12	50^{+60}_{-18} ms	113–44 ms	675–267 ms
^{290}115	9.92–10.42	$0.24^{+0.28}_{-0.09}$ s	17.73–0.66 s	97.73–3.87 s
^{286}113	9.75–9.89	$8.7^{+10.4}_{-3.1}$ s	11.2–4.3 s	65.3–25.6 s
^{282}Rg	9.13–9.31	40^{+49}_{-14} s	161–43 s	974–266 s
^{278}Mt	9.52–9.69	$5.2^{+6.2}_{-1.8}$ s	1.7–0.5 s	13.6–4.4 s
^{274}Bh	8.82–8.93	54^{+65}_{-19} s	44–19 s	362–161 s
^{261}Rf^m	8.65(5)	7.8±3.2 s	8.5 s	40.3 s

As one can see from the table, the decay energies of α decay chains originating from ^{288}115 and ^{293,294}117 are ambiguous and their values are restricted in a certain range, owing to the paucity of the observed events. The calculated α decay half-life, intensely sensitive to the decay energy, is correspondingly located in the range which appropriately involves the experimental half-life. Furthermore, there seems to be two possible ranges of α decay energy respectively for ^{274}Mt and ^{284}113 according to the new experiment [11], and we have chosen one of them for each nucleus via the estimation in the recent mass table [37]. Besides the consistency of the calculation with the measurement for these isotopes, the evaluated α-decay half-lives are found to be in good agreement with the new or improved experimental ones, such as the special cases of the attractive nucleus ^{270}Hs and a supposed isomeric state in ^{261}Rf. There is an abnormal discrepancy in the calculated and measured half-lives for ^{279}Rg. This situation may be caused by the large error bar (0.16 MeV) of the decay energy, and the nonzero angular momentum of the emitted α particle may need to be introduced in the calculation.

Except for the superheavy α emitters with a large range of α decay energies, the overall agreement of calculated α decay half-lives with available experimental data in the Table I and II can be estimated by the standard deviation $\sigma = \sqrt{\sum_{i=1}^{30}(\log_{10} T_{\rm expt}^i - \log_{10} T_{\rm calc}^i)^2} = 0.489$, even including the mentioned abnormal case of ^{271}Rg. Generally, for either large or narrow decay widths, these newly measured data of exotic α decays are reasonably reproduced as can be seen in Tables I and II. This further proves the basic validity of the MTPA for deformed nuclei within the density-dependent cluster model.

IV. SUMMARY

In summary, the modified two-potential approach for deformed nuclei combined with a cluster model is employed to systematically investigate the new α decay data of recently proposed experiments in two interesting cases: the α transitions from very proton-rich nuclei near the proton drip line and from the heaviest isotopes. Reasonable agreement between theory and experiment is achieved, which indicates that the present model is valid for the studied mass region. Meanwhile, the phenomenological expression is used to evaluate the α decay half-lives for comparison. Besides being considered as a further test of applicability of the model, the present work is expected to be useful for subsequent experiments of extreme nuclei in the neutron-deficient and heaviest regimes.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (Grants No. 11035001, No. 10975072, No. 10735010, No. 11375086, and No. 11120101005), by the 973 National Major State Basic Research and Development of China (Grants No. 2010CB327803 and No. 2013CB834400), by CAS Knowledge Innovation Project No. KJCX2-SW-N02, by Research Fund of Doctoral Point (RFDP) Grant No. 20100091110028, and by a project funded by the Priority Academic Programme Development of JiangSu Higher Education Institutions (PAPD).

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