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α-decay half-lives of ground and isomeric states of exotic nuclei around closed shells

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We investigate the α-decay half-lives of ground and isomeric states of exotic nuclei around the shell closures $Z = 82$ and $N = 82$ by the density-dependent cluster model (DDCM). Our calculations concentrate on four kinds of favored α transitions: (1) ground state to ground state, (2) ground state to isomeric state, (3) isomeric state to ground state, and (4) isomeric state to isomeric state. The calculated α-decay half-lives of both ground and isomeric states are found to be in good agreement with the experimental data. Useful predictions on the partial half-lives of several α emitters are made for future experiments.

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Nowadays, α decay has become a powerful tool to investigate the structural properties of unstable nuclei in the mass table, especially for drip-line nuclei, closed-shell nuclei, and superheavy nuclei [1,2]. Extensive theoretical studies have been devoted to pursuing a quantitative description of α decay by both phenomenological and microscopic methods. For instance, Buck *et al.* systematically calculated the α-decay half-lives of nuclei by using the Cosh potential [3]. Royer also made a systematic calculation of the α-decay half-lives with the generalized liquid drop model [4]. Delion and co-workers analyzed the α decays of deformed heavy and superheavy nuclei microscopically [5]. Mohr studied the α-nucleus potentials and α-decay half-lives for superheavy nuclei [6]. Recently, we performed a series of calculations on half-lives of α emitters in the whole chart of nuclides [7]. Other theoretical studies have also been performed to investigate the α-decay half-lives (see Refs. [8–15] and references therein).

Usually most α-decay calculations are concentrated on the ground state to ground state transitions, which are the primary decay pattern of all even-even nuclei and parts of odd-A and odd-odd nuclei. For such favored α transitions, the treatment of both excitation energy and centrifugal potential is relatively easier in calculations. Besides these α transitions, the ground state of many odd-A and odd-odd nuclei can also decay to the excited states of their daughter nuclei because the ground state to ground state transitions are strongly hindered by the nonzero angular momentum of the α particle [16]. Moreover, there also exists an important kind of α transition around the proton and neutron closed shells (i.e., α decay of isomeric states). Such α transitions can provide useful information on the internal structure properties of nuclei near the closed shells. Although the experimental data of the islands of isomerism have accumulated in recent years [1,2], theoretical studies on α decay of isomeric states are very rare compared with those of the ground-state α transitions.

In this Brief Report, we present a detailed analysis of both ground and isomeric α decays of exotic nuclei around the proton and neutron shell closures by the density-dependent cluster model (DDCM). The density-dependent cluster model is based on the microscopic double-folding potential with the M3Y nucleon-nucleon interaction [17] and the well-established two-potential approach [18]. By using the DDCM, we systematically calculate the half-lives of four kinds of α transitions for Ho, Tm, Lu, Bi, Po, At, and Rn isotopic chains. The influences of decay energy, angular momentum, and deformation parameter on the α-decay half-lives are analyzed and discussed in detail. The theoretical α-decay half-lives of several nuclei are also predicted for future experiments.

First, we briefly introduce the framework of the density-dependent cluster model. In the DDCM, the α cluster is considered to penetrate the deformed Coulomb barrier after its formation in the parent nucleus. The sum of the nuclear potential, the Coulomb potential, and the centrifugal potential between the α particle and the core is given by [7]

$$V_{\text{Total}}(R,\theta) = V_N(R,\theta) + V_C(R,\theta) + \frac{\hbar^2}{2\mu}\frac{\left(\ell+\frac{1}{2}\right)^2}{R^2}, \quad (1)$$

where R is the distance between the mass centers of the α particle and the core and θ is the orientation angle of the α particle with respect to the symmetry axis of the daughter nucleus. The nuclear potential is obtained from the double-folding integral of the M3Y nucleon-nucleon interaction with the matter density distributions of the α particle and the core [17]. The mass density distribution of the daughter nucleus is a deformed Fermi distribution with standard parameters [7]

$$\rho_2(r_2,\theta) = \rho_0\left\{1+\exp\left[\frac{r_2 - R_0[1+\beta_2 Y_{20}(\theta)+\beta_4 Y_{40}(\theta)]}{a}\right]\right\}, \quad (2)$$

where the parameters $R_0 = 1.07A_d^{1/3}$ fm and $a = 0.54$ fm. The double-folding potential can be evaluated by a sum of different multipole components [7],

$$V_{N\,\text{or}\,C}(R,\theta) = \sum_{l=0,2,4,\ldots} V^l_{N\,\text{or}\,C}(R,\theta), \quad (3)$$

and the multipole component of the double-folding potential is written as [19]

$$V^l_{N\,\text{or}\,C}(R,\theta) = \frac{2}{\pi}[(2l+1)/4\pi]^{1/2}\int_0^\infty dk k^2 j_l(kR) \times \tilde{\rho}_1(k)\tilde{\rho}_2{}^{(l)}(k)\tilde{v}(k)P_l(\cos\theta), \quad (4)$$

where $\tilde{\rho}_1(k)$ is the Fourier transformation of the density distribution of the α particle, $\tilde{\rho}_2^{(l)}(k)$ is the intrinsic form factor corresponding to the daughter nucleus, $\tilde{v}(k)$ is the Fourier transformation of the effective M3Y interaction or the proton-proton Coulomb interaction, and $P_l(\cos\theta)$ is the Legendre function of degree l. The polar-angle-dependent penetration probability of α decay in the deformed version of the DDCM can be given by [7]

$$\mathcal{P}_\theta = \exp\left[-2\int_{R_2(\theta)}^{R_3(\theta)} \sqrt{\frac{2\mu}{\hbar^2}\,|Q_\alpha - V_{\mathrm{Total}}(R,\theta)|}\,dR\right], \qquad (5)$$

where $R_2(\theta)$ and $R_3(\theta)$ are the second and third classical turning points of a certain orientation angle θ and Q_α is the experimental α-decay energy with the standard electron shielding correction included. The total penetration probability $\mathcal{P}_{\mathrm{Total}}$ is obtained by averaging P_θ in all directions [7]. Finally, the α-decay width in the deformed version of the DDCM is given by [7]

$$\Gamma = P_\alpha\,\mathcal{F}\,\frac{\hbar^2}{4\mu}\frac{1}{2}\int_0^\pi \mathcal{P}_\theta \sin(\theta)\mathrm{d}\theta, \qquad (6)$$

where $\mathcal{F}$ is the normalization factor and P_α is the α-cluster preformation factor in the parent nucleus, which is chosen to fit the experimental half-lives ($P_\alpha = 0.38$ for even-even nuclei, $P_\alpha = 0.24$ for odd-A nuclei, and $P_\alpha = 0.13$ for odd-odd nuclei). These values are consistent with both the experimental facts and the microscopic calculations [20,21].

Before presenting the detailed theoretical results, we would like to briefly discuss the depth of the α-core potential. In the DDCM, the depth of the nuclear potential is determined by employing the Bohr-Sommerfeld (BS) condition $\int_{R_1}^{R_2} dr\sqrt{\frac{2\mu}{\hbar^2}[Q - V(r)]} = (G - L + 1)\frac{\pi}{2}$ [7]. The global quantum number is chosen as $G = 18$ and the angular momentum of the α particle, L, is zero for all α emitters. By inputting the experimental α-decay energy, the depth of the nuclear potential, that is, the normalization factor λ, can be easily obtained from the BS condition [7]. In fact, the variation of the normalization factor is rather small for different α emitters. For instance, its value varies only from $\lambda = 0.63005$ to 0.63669 for 20 exotic α decays near the closed shell $N = 82$ (^{151}Ho–^{158}Lu). Thus the depth of the nuclear potential is not a free parameter in the DDCM and the purpose of using the BS condition is not to fit the experimental data, but rather to generate a quasibound state for each decay. In addition, we note that the values of all parameters in the DDCM (e.g., $P_\alpha, G, L, \ldots$) are the same as those in the global calculations [7] and we do not introduce any additional parameter here.

We have performed systematic calculations on half-lives of α emitters near closed shells $N = 82$ and $Z = 82$, respectively. In Table I, we list the theoretical results of the exotic isotopic chains around $N = 82$ (i.e., the Ho, Tm, and Lu isotopes). The first and second columns of Table I denote the parent nucleus and its neutron number. The third and fourth columns are the spins and parities of the parent and daughter nuclei, respectively. The experimental α-decay energy and the deformation parameters of the core are given in the fifth to seventh columns. The experimental and theoretical α-decay half-lives are listed in the last two columns.

TABLE I. The experimental and theoretical α-decay half-lives of the ground and isomeric transitions of nuclei near the neutron shell closure $N = 82$ (in seconds).

Decay	N_p	I_i^π	I_f^π	Q (MeV)	β_2	β_4	T_α (Exp)	T_α (Cal)
$^{151}\mathrm{Ho} \to {}^{147}\mathrm{Tb}^m + \alpha$	84	$11/2^-$	$11/2^-$	4.645	−0.008	0.000	1.60×10^2	1.28×10^2
$^{151}\mathrm{Ho}^m \to {}^{147}\mathrm{Tb} + \alpha$	84	$1/2^+$	$1/2^+$	4.737	−0.008	0.000	6.13×10^1	4.24×10^1
$^{152}\mathrm{Ho} \to {}^{148}\mathrm{Tb} + \alpha$	85	2^-	2^-	4.507	−0.052	0.001	1.35×10^3	1.25×10^3
$^{152}\mathrm{Ho}^m \to {}^{148}\mathrm{Tb}^m + \alpha$	85	9^+	9^+	4.577	−0.052	0.001	4.58×10^2	5.15×10^2
$^{153}\mathrm{Ho} \to {}^{149}\mathrm{Tb}^m + \alpha$	86	$11/2^-$	$11/2^-$	4.015	−0.044	0.001	2.35×10^5	6.40×10^5
$^{153}\mathrm{Ho}^m \to {}^{149}\mathrm{Tb} + \alpha$	86	$1/2^+$	$1/2^+$	4.119	−0.044	0.001	3.10×10^5	1.35×10^5
$^{154}\mathrm{Ho} \to {}^{150}\mathrm{Tb} + \alpha$	87	2^-	2^-	<4.042	0.143	0.016	3.71×10^6	$>5.67 \times 10^5$
$^{153}\mathrm{Tm} \to {}^{149}\mathrm{Ho} + \alpha$	84	$11/2^-$	$11/2^-$	5.248	−0.008	0.001	1.63×10^0	1.66×10^0
$^{153}\mathrm{Tm}^m \to {}^{149}\mathrm{Ho}^m + \alpha$	84	$1/2^+$	$1/2^+$	5.242	−0.008	0.001	2.69×10^0	1.76×10^0
$^{154}\mathrm{Tm} \to {}^{150}\mathrm{Ho} + \alpha$	85	2^-	2^-	5.094	−0.052	0.002	1.50×10^1	1.49×10^1
$^{154}\mathrm{Tm}^m \to {}^{150}\mathrm{Ho}^m + \alpha$	85	9^+	9^+	5.175	−0.052	0.002	5.69×10^0	6.18×10^0
$^{155}\mathrm{Tm} \to {}^{151}\mathrm{Ho} + \alpha$	86	$11/2^-$	$11/2^-$	4.569	−0.035	0.002	1.14×10^3	4.06×10^3
$^{155}\mathrm{Tm}^m \to {}^{151}\mathrm{Ho}^m + \alpha$	86	$1/2^+$	$1/2^+$	4.569	−0.035	0.002	Un	4.06×10^3
$^{156}\mathrm{Tm} \to {}^{152}\mathrm{Ho} + \alpha$	87	2^-	2^-	4.340	0.126	0.016	1.31×10^5	1.25×10^5
$^{155}\mathrm{Lu} \to {}^{151}\mathrm{Tm} + \alpha$	84	$11/2^-$	$11/2^-$	5.803	0.000	0.000	7.80×10^{-2}	7.01×10^{-2}
$^{155}\mathrm{Lu}^m \to {}^{151}\mathrm{Tm}^m + \alpha$	84	$1/2^+$	$1/2^+$	5.731	0.000	0.000	1.82×10^{-1}	1.37×10^{-1}
$^{156}\mathrm{Lu} \to {}^{152}\mathrm{Tm} + \alpha$	85	2^-	2^-	5.595	−0.052	0.000	Un	8.70×10^{-1}
$^{156}\mathrm{Lu}^m \to {}^{152}\mathrm{Tm}^m + \alpha$	85	9^+	9^+	5.715	−0.052	0.000	2.11×10^{-1}	2.75×10^{-1}
$^{157}\mathrm{Lu} \to {}^{153}\mathrm{Tm}^m + \alpha$	86	$1/2^+$	$1/2^+$	5.064	−0.018	0.000	Un	1.26×10^2
$^{157}\mathrm{Lu}^m \to {}^{153}\mathrm{Tm} + \alpha$	86	$11/2^-$	$11/2^-$	5.128	−0.018	0.000	7.98×10^1	6.14×10^1
$^{158}\mathrm{Lu} \to {}^{154}\mathrm{Tm} + \alpha$	87	2^-	2^-	4.790	0.116	0.009	1.14×10^3	4.79×10^3

From Table I, we can see that the ground and isomeric states of these α emitters mainly decay to the corresponding states of the daughter nuclei with the same spins and parities. Other transitions are strongly hindered by the large angular momentum of the α particle ($L = 5$ for odd-A nuclei and $L = 7$ for odd-odd nuclei). Such an exotic decay pattern of the Ho, Tm, and Lu isotopes is due to the effect of the closed shell at $N = 82$, which provides a good opportunity to study the isomeric α transitions of unstable nuclei. In Table I, the α-decay energies of both ground and isomeric transitions are taken from Refs. [1,2]. The deformation parameters are taken from Möller *et al.*'s calculations [22]. We can see that the magnitude of nuclear deformation generally increases with increasing neutron number for each isotopic chain. Their influences on α-decay half-lives are properly taken into account in our calculations. The experimental lifetimes of the isomeric states are comparable to the ground-state ones. In some cases, they are even longer than the ground-state lifetimes. It is seen from Table I that the α-decay half-lives calculated by the DDCM are very close to the experimental data for both the ground and isomeric states. The deviation between theory and data is generally within a factor of 3. For the nucleus ^{154}Ho, the experimental α-decay energy is unavailable and the lower limit of its α-decay half-life is estimated by the DDCM. Moreover, the theoretical α-decay half-lives of ^{155}Tm^m, ^{156}Lu, and ^{157}Lu are predicted for future experiments (marked with the symbol "Un").

In Table II, we give the theoretical results of the ground and isomeric states of exotic nuclei around the proton shell closure $Z = 82$ (i.e., the Bi, Po, At, and Rn isotopes). We can see from Table II that the decay pattern of Bi isotopes is very similar to those of the Ho isotopic chains. However, this is not the case for

TABLE II. The experimental and theoretical α-decay half-lives of the ground and isomeric transitions of nuclei near the proton shell closure $Z = 82$ (in seconds).

Decay	Z_p	I_i^π	I_f^π	Q (MeV)	β_2	β_4	T_α (Exp)	T_α (Cal)
^{187}Bi $\to$ ^{183}Tl^m + α	83	9/2$^-$	9/2$^-$	7.140	−0.053	0.000	7.00×10^{-2}	9.39×10^{-2}
^{187}Bi^m $\to$ ^{183}Tl + α	83	1/2$^+$	1/2$^+$	7.750	−0.053	0.000	8.00×10^{-4}	1.02×10^{-3}
^{189}Bi $\to$ ^{185}Tl^m + α	83	9/2$^-$	9/2$^-$	6.816	−0.053	0.000	1.43×10^{0}	1.25×10^{0}
^{189}Bi^m $\to$ ^{185}Tl + α	83	1/2$^+$	1/2$^+$	7.362	−0.053	0.000	1.00×10^{-2}	1.58×10^{-2}
^{191}Bi $\to$ ^{187}Tl^m + α	83	9/2$^-$	9/2$^-$	6.446	−0.053	0.000	2.06×10^{1}	3.11×10^{1}
^{191}Bi^m $\to$ ^{187}Tl + α	83	1/2$^+$	1/2$^+$	7.023	−0.053	0.000	3.00×10^{-1}	2.08×10^{-1}
^{193}Bi $\to$ ^{189}Tl^m + α	83	9/2$^-$	9/2$^-$	6.024	−0.053	0.001	1.40×10^{3}	1.79×10^{3}
^{193}Bi^m $\to$ ^{189}Tl + α	83	1/2$^+$	1/2$^+$	6.612	−0.053	0.001	3.56×10^{0}	6.42×10^{0}
^{195}Bi $\to$ ^{191}Tl^m + α	83	9/2$^-$	9/2$^-$	5.534	−0.053	0.000	6.10×10^{5}	3.64×10^{5}
^{195}Bi^m $\to$ ^{191}Tl + α	83	1/2$^+$	1/2$^+$	6.234	−0.053	0.000	2.64×10^{2}	2.04×10^{2}
^{195}Po $\to$ ^{191}Pb + α	84	3/2$^-$	3/2$^-$	6.750	0.000	0.000	6.19×10^{0}	5.34×10^{0}
^{195}Po^m $\to$ ^{191}Pb^m + α	84	13/2$^+$	13/2$^+$	6.842	0.000	0.000	2.13×10^{0}	2.40×10^{0}
^{197}Po $\to$ ^{193}Pb + α	84	3/2$^-$	3/2$^-$	6.410	0.000	0.000	1.27×10^{2}	1.10×10^{2}
^{197}Po^m $\to$ ^{193}Pb^m + α	84	13/2$^+$	13/2$^+$	6.514	0.000	0.000	3.10×10^{1}	4.16×10^{1}
^{199}Po $\to$ ^{195}Pb + α	84	3/2$^-$	3/2$^-$	6.074	0.009	0.001	2.74×10^{3}	2.84×10^{3}
^{199}Po^m $\to$ ^{195}Pb^m + α	84	13/2$^+$	13/2$^+$	6.181	0.009	0.001	6.35×10^{2}	9.58×10^{2}
^{201}Po $\to$ ^{197}Pb + α	84	3/2$^-$	3/2$^-$	5.799	0.000	0.000	5.74×10^{4}	5.01×10^{4}
^{201}Po^m $\to$ ^{197}Pb^m + α	84	13/2$^+$	13/2$^+$	5.904	0.000	0.000	1.84×10^{4}	1.58×10^{4}
^{196}At $\to$ ^{192}Bi + α	85	3$^+$	3$^+$	7.205	−0.052	0.000	Un	5.69×10^{-1}
^{196}At^m $\to$ ^{192}Bi^m + α	85	10$^-$	10$^-$	7.024	−0.052	0.000	Un	2.49×10^{0}
^{198}At $\to$ ^{194}Bi + α	85	3$^+$	3$^+$	6.895	−0.052	0.000	Un	6.92×10^{0}
^{198}At^m $\to$ ^{194}Bi^m + α	85	10$^-$	10$^-$	6.995	−0.052	0.000	Un	2.97×10^{0}
^{200}At $\to$ ^{196}Bi + α	85	(2, 3)$^+$	(2, 3)$^+$	6.596	−0.052	−0.001	7.58×10^{1}	9.15×10^{1}
^{200}At^m $\to$ ^{196}Bi^m + α	85	7$^+$	7$^+$	6.542	−0.052	−0.001	1.09×10^{2}	1.51×10^{2}
^{200}At^n $\to$ ^{196}Bi^n + α	85	10$^-$	10$^-$	6.670	−0.052	−0.001	3.33×10^{1}	4.70×10^{1}
^{202}At $\to$ ^{198}Bi + α	85	(2, 3)$^+$	(2, 3)$^+$	6.353	−0.052	0.001	1.02×10^{3}	8.50×10^{2}
^{202}At^m $\to$ ^{198}Bi^m + α	85	7$^+$	7$^+$	6.259	−0.052	0.001	2.09×10^{3}	2.14×10^{3}
^{202}At^n $\to$ ^{198}Bi^n + α	85	10$^-$	10$^-$	6.402	−0.052	0.001	Un	5.28×10^{2}
^{197}Rn $\to$ ^{193}Po + α	86	3/2$^-$	3/2$^-$	7.415	−0.215	0.002	6.60×10^{-2}	9.21×10^{-2}
^{197}Rn^m $\to$ ^{193}Po^m + α	86	13/2$^+$	13/2$^+$	7.505	−0.215	0.002	2.10×10^{-2}	4.63×10^{-2}
^{199}Rn $\to$ ^{195}Po + α	86	3/2$^-$	3/2$^-$	7.125	0.071	−0.001	Un	1.40×10^{0}
^{199}Rn^m $\to$ ^{195}Po^m + α	86	13/2$^+$	13/2$^+$	7.205	0.071	−0.001	Un	7.29×10^{-1}
^{201}Rn $\to$ ^{197}Po + α	86	3/2$^-$	3/2$^-$	6.860	0.062	−0.002	8.97×10^{0}	1.27×10^{1}
^{201}Rn^m $\to$ ^{197}Po^m + α	86	13/2$^+$	13/2$^+$	6.936	0.062	−0.002	4.22×10^{0}	6.55×10^{0}
^{203}Rn $\to$ ^{199}Po + α	86	3/2$^-$	3/2$^-$	6.630	0.000	0.000	7.03×10^{1}	9.92×10^{1}
^{203}Rn^m $\to$ ^{199}Po^m + α	86	13/2$^+$	13/2$^+$	6.681	0.000	0.000	Un	6.22×10^{1}

the Po, At, and Rn isotopes. Because the parent and daughter nuclei have the same ground and isomeric state configurations, the ground state to ground state or the isomeric state to isomeric state α transitions are much favored by these α emitters, similar to the decays of Tm and Lu isotopes. More interestingly, the α transitions from two isomeric states of the same parent nucleus are observed in experiments (^{200}At and ^{202}At). These α transitions can be used to check the validity of current α-decay models based on nuclear data of ground states. From Table II, we can see that the experimental α-decay energies of ground and isomeric states differ from each other for the Bi isotopes. For other cases, the values of α-decay energies are very close to each other. It is also seen from Table II that these α emitters are generally spherical nuclei, except the nucleus ^{197}Rn, which has a core deformation of $\beta_2 = -0.215$ [22]. Although the variation of experimental α-decay half-lives is as large as a factor of 10^9, the theoretical results of the DDCM agree with the experimental data very well. The largest deviation occurs for the decay $^{197}\mathrm{Rn}^m \rightarrow {}^{193}\mathrm{Po}^m + \alpha$. The experimental α-decay lifetime of $^{197}\mathrm{Rn}^m$ is 21.0 ms and its corresponding theoretical value is 46.3 ms. The agreement between theory and data for other α emitters is generally within a factor of 2. This shows that the DDCM has very good accuracy for α transitions of both the ground and isomeric states. Furthermore, we predict the partial α-decay half-lives for a series of nuclei ^{196}At, $^{196}\mathrm{At}^m$, ^{198}At, $^{198}\mathrm{At}^m$, $^{202}\mathrm{At}^n$, ^{199}Rn, $^{199}\mathrm{Rn}^m$, and $^{203}\mathrm{Rn}^m$, for which the experimental data are still unavailable. Because of the success of the DDCM for the measured data, the present exploration to unknown cases is necessary and useful for experiments.

To conclude, we have systematically studied the α-decay half-lives of ground and isomeric states of the exotic nuclei near the closed shells $Z = 82$ and $N = 82$ by the density-dependent cluster model. The good agreement between experimental and theoretical results shows that the DDCM is not only valid for ground state α transitions but also for isomeric state α transitions. Useful predictions on the partial half-lives of several α emitters are made by the DDCM. It will be very interesting to compare the present theoretical predictions with the experimental observations in future.

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