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Hindered α-transitions in Odd-Z Superheavy Nuclei

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Abstract: We investigate the α-transition of odd-Z superheavy nuclei by the density-dependent cluster model (DDCM). The microscopic nuclear potential between the α-particle and the daughter nucleus is evaluated numerically from the double-folding model with the standard M3Y nucleon-nucleon interaction. The Coulomb potential is also obtained from the double-folding integral of the proton-proton Coulomb interaction with the charge density distributions of α-particle and daughter nucleus. From our calculations, enhanced stability against α-decays is found for the odd-Z superheavy nuclei due to the hindrance effect of non-zero angular momentum and the small preformation factor of the α-particle.

Key words: α-transition; superheavy nuclei; cluster model

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1 Introduction

The synthesis of new superheavy nuclei has been a hot topic in nuclear physics in recent years[1]. A number of superheavy nuclei have been successfully synthesized in various large laboratories in Germany, Russia, China, Japan, and USA etc.[2–14]. For these newly synthesized superheavy nuclides, it is of particular interest to study their α-decay properties, such as the α-decay energies and half-lives. From the theoretical viewpoint, the calculation of α-transitions of the odd-Z superheavy nuclei could be much more complex than that of even-even ones because it is difficult to treat the problem of angular momentum in these nuclei. The new experimental data on the odd-Z superheavy nuclei provide us a good opportunity to investigate their stability and structure properties.

To investigate the α-transitions in odd-Z supheavy nuclei, we use the density-dependent cluster model (DDCM) to caluclate their half-lives. In DDCM, the effective potential between α-cluster and daughter-nucleus is obtained from a double folded integral of the renormalized M3Y potential with the density distributions of the α-particle and daughter nucleus[15]. We also include the exchange term to the M3Y interaction to guarantee the anti-symmetrization of identical particles in the α-cluster and in the core[16]. The depth of the nuclear potential λ is carefully adjusted to reproduce the experimental α-decay energy by application of the well-known Bohr-Sommerfeld condition[15]. The only free parameter in DDCM is the preformation factor of the α-particle in the parent nucleus[15]. The α-decay width can be obtained from the well-established two-potential approach, in which the pre-exponential factor is defined explicitly[17–19]. From the large scale of numerical calculations of medium and heavy nuclei with available data, the DDCM has shown to be very reliable for α-decay half-life calculations. Here we focus on the α-decay half-lives of several odd-Z superheavy nuclei by using the DDCM. The renewed experimental α-decay energies of odd-Z superheavy nuclei are used in calculations. The influence of both the preformation factor and the angular momentum on the α-decay half-lives of odd-Z superheavy nuclei is discussed in detail.

The outline of this paper is as follows. In section 2, we briefly introduce the framework of the DDCM. The corresponding results and discussions are presented in section 3. A brief summary is given in the last section.

2 Formalism

In the DDCM, the ground state of parent nucleus is

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assumed to be an α-particle (or cluster) orbiting the daughter nucleus. The α- (or cluster-) core potential is the sum of the nuclear potential, the Coulomb potential and the centrifugal potential[15]

$$V(R) = V_{\mathrm{N}}(R) + V_{\mathrm{C}}(R) + \frac{\hbar^2}{2\mu}\frac{\left(L+\frac{1}{2}\right)^2}{R^2} , \qquad (1)$$

where $V_{\mathrm{N}}(R)$ and $V_{\mathrm{C}}(R)$ are the double-folding nuclear and Coulomb potentials, respectively. The nuclear and Coulomb potentials are microscopically determined in which the input parameters, such as the radius and the diffuseness, are all taken from the classical nuclear textbooks. The renormalized factor λ in $V_{\mathrm{N}}(R)$ is determined separately for each decay by applying the Bohr-Sommerfeld quantization condition[15]

$$V_{\mathrm{N}}(R) = \lambda \int \mathrm{d}\boldsymbol{r}_1\, \mathrm{d}\boldsymbol{r}_2 \rho_1(\boldsymbol{r}_1)\rho_2(\boldsymbol{r}_2)\, g(E,|\boldsymbol{s}|) . \qquad (2)$$

The mass density distribution of the spherical α-particle ρ_1 is a standard Gaussian form given by Satchler and Love[20]. The mass density distribution of the daughter nucleus ρ_2 is a deformed Fermi distribution with standard parameters. The M3Y nucleon-nucleon interaction is given by two direct terms with different ranges, and by an exchange term with a delta interaction[16]

$$\begin{aligned} g(E,|\boldsymbol{s}|) =& 7999\frac{\exp(-4s)}{4s} \\ & - 2134\frac{\exp(-2.5s)}{2.5s} + J_{00}\delta(\boldsymbol{s}) , \end{aligned} \qquad (3)$$

$$J_{00} = -276\left(1 - 0.005\frac{E_\alpha}{A_\alpha}\right) . \qquad (4)$$

The renormalized factor λ in the nuclear potential is determined separately for each decay by applying the Bohr-Sommerfeld quantization condition.

$$\int_{R_1}^{R_2} \mathrm{d}r \sqrt{\frac{2\mu}{\hbar^2}\left[Q - V(r)\right]} = (2n+1)\frac{\pi}{2} = (G - L + 1)\frac{\pi}{2} . \qquad (5)$$

The Coulomb potential is obtained from the double-folding integral of the proton-proton Coulomb interaction with the charge density distributions of α particle and daughter nucleus[15]

$$\mathrm{V}_{\mathrm{C}}(R) = \int \mathrm{d}\boldsymbol{r}_1\, \mathrm{d}\boldsymbol{r}_2 \frac{e^2}{\left|R + \boldsymbol{r}_2 - \boldsymbol{r}_1\right|}\rho_1'(\boldsymbol{r}_1)\rho_2'(\boldsymbol{r}_2) . \qquad (6)$$

In quasiclassical approximation, the α-decay width $\varGamma$ is given by[17]

$$\varGamma = P_\alpha \frac{\hbar^2}{4\mu} \frac{\exp\left[-2\int_{R_2}^{R_3} \mathrm{d}R\, K(R)\right]}{\int_{R_1}^{R_2} \mathrm{d}R \frac{1}{K(R)} \cos^2\left(\int_{R_1}^{R} \mathrm{d}R' K(R') - \frac{\pi}{4}\right)} . \qquad (7)$$

Finally the α-decay half-life is then related to the width by[15]

$$T_{1/2} = \frac{\hbar \ln 2}{\varGamma} . \qquad (8)$$

3 Results

We have made calculations on the half-lives of odd-Z superheavy nuclei $^{278}113$, $^{280,\,279,\,274}111$, and $^{266}107$ by the DDCM. Firstly, we assume that the α-transitions of these odd-Z superheavy nuclei are favored, which means that the angular momentum carried away by the α-particle is zero. The corresponding results of the DDCM are presented in Table 1. In Table 1, the first three columns are the mass number, proton number, and neutron number of the parent nuclei, respectively. The experimental and theoretical α-decay half-lives are given in the fourth and fifth columns, respectively. We define the hinderance factor as the ratio of the experimental half-life to the calculated one $\left(HF = \frac{T_{\mathrm{Exp.}}}{T_{\mathrm{Cal.}}}\right)$ where the preformation factor of the α-particle is fixed to 1.0. The obtained HF factor of each α-transition is given in the sixth column.

Table 1 Hinderance factors and extracted preformation factors of the odd-*Z* superheavy nuclei. The unit of the α-decay half-lives is in seconds

A	Z	N	$T_\alpha^{\mathrm{Exp.}}$	$T_\alpha^{\mathrm{Cal.}}$	HF	P_α
278	113	165	1.8×10^{-3}	4.2×10^{-5}	42.9	0.023
280	111	169	3.6×10^{0}	2.5×10^{-1}	14.7	0.068
279	111	168	1.7×10^{-1}	5.2×10^{-3}	32.9	0.030
274	111	163	1.5×10^{-2}	3.2×10^{-5}	471.0	0.002 1
266	107	159	1.3×10^{0}	1.2×10^{-2}	112.6	0.008 9

We can see from the HF factor in Table 1 that all the experimental half-lives are underestimated by the DDCM. One possible reason of the deviation between model and data is that the preformation factors of these odd-Z nuclei are much smaller than 1.0. Thus, the proper preformation factors needed to reproduce the experimental data are given in the last column of Table 1 ranging from 0.0021 to 0.068.

Another possible reason of the large deviation between model and data is the influence of the angular momentum carried away by the α-particle. To study the effects of angular momentum, we fix the values of P_α taken from the global calculation for the heavy and superheavy nuclei[15]. For the even-odd nuclei, we still use $P_\alpha = 0.60$ in calculations and a relatively smaller value $P_\alpha = 0.35$ is used for the odd-odd superheavy nuclei owing to the blocking effect of the last odd nucleon[15]. The detailed theoretical results of α-decay half-lives with different values of angular momentum are given in Table 2. In Table 2, the first column denotes the parent nuclei. The experimental α-decay energies are given in the second column. One can see from Table 2 that the experimental α-decay energy Q_α varies from 9.938 MeV to 11.737 MeV. It is noted that the calculated α-decay half-lives are very sensitive to the decay energy and a change of 1.0 MeV in the Q_α value may result in a change of several orders of the magnitude of the α-decay half-lives. Thus the reliable α-decay energies are needed to calculate their half-lives. The global number G and the angular momentum L are given in the third column. The experimental and theoretical α-decay half-lives are listed in the last two column of Table 2, respectively. We can also see from Table 2 that the deviation between experimental and calculated half-lives is large if zero angular momentum is assumed for these nuclei. As we know, the angular momentum carried by the α-particle will be non-zero in the cases of hindered transitions. As a test, we assume that the angular momentum of the α-particle is $l = 3$ or $l = 5$ in the transitions. And we can see that the agreement between experimental and calculated α-decay half-lives is improved greatly by taking the non-zero angular momentum into account. To see the effects of angular momentum on α-decay half-lives more clearly, we plot in Fig. 1 the variation of the α-decay half-lives with different angular momentum values. It is clearly seen from both Fig. 1 and Table 2 that the stability of these odd-Z superheavy nuclei against α-decay is enhanced greatly due to the effects of the non-zero angular momentum.

Table 2　Experimental and theoretical α-decay half-lives of odd-Z superheavy nuclei. The unit of the α-decay half-lives is in seconds

Nuclei	Q_α/MeV	(G, L)	$T_\alpha^{\mathrm{Exp.}}$	$T_\alpha^{\mathrm{Cal.}}$
$^{278}113$	11.737	(20, 0)	1.8×10^{-3}	1.2×10^{-4}
		(20, 3)	1.8×10^{-3}	3.3×10^{-4}
		(20, 5)	1.8×10^{-3}	1.5×10^{-3}
$^{280}111$	9.938	(20, 0)	3.6×10^{0}	7.0×10^{-1}
		(20, 3)	3.6×10^{0}	2.0×10^{0}
		(20, 5)	3.6×10^{0}	9.2×10^{0}
$^{279}111$	10.568	(20, 0)	1.7×10^{-1}	8.6×10^{-3}
		(20, 3)	1.7×10^{-1}	2.4×10^{-2}
		(20, 5)	1.7×10^{-1}	1.1×10^{-1}
$^{274}111$	11.525	(20, 0)	1.5×10^{-2}	9.1×10^{-5}
		(20, 3)	1.5×10^{-2}	2.5×10^{-4}
		(20, 5)	1.5×10^{-2}	1.1×10^{-3}
$^{266}107$	9.964	(20, 0)	1.3×10^{0}	3.3×10^{-2}
		(20, 3)	1.3×10^{0}	9.2×10^{-2}
		(20, 5)	1.3×10^{0}	4.5×10^{-1}

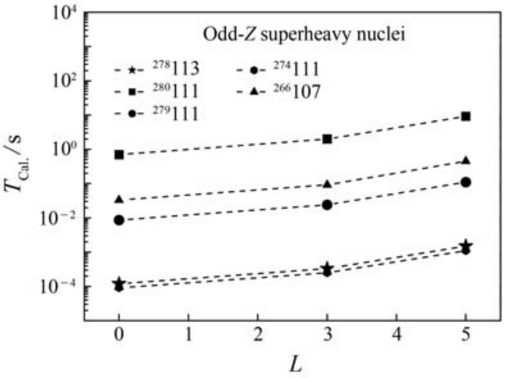

Fig. 1　Variation of the α-decay half-lives with different angular momentum carried by the α-particle for odd-Z superheavy nuclei.

4　Summary

In summary, we have investigated the α-transitions of odd-Z superheavy nuclei by the DDCM. Although the α-decay energy plays the key role in all α-decay calculations, the effects of both the preformation factor of α-particle and the angular momentum also need to be properly taken into account. By using DDCM, the theoretical α-decay half-lives are calculated with different values of preformation factor and angular momentum. It is found that the agreement between theory and experiment is improved greatly either by using small preformation factors or non-zero angular momentum for these odd-Z superheavy nuclei.

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奇 *Z* 超重核的禁戒 α 衰变

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摘要： 采用密度依赖的结团模型研究了奇 Z 超重核的禁戒 α 衰变，α 粒子与子核之间的微观核势通过双折叠模型对 M3Y 核子-核子相互作用势以及 α 粒子与子核的密度积分给出。α 粒子与子核之间的库仑相互作用也通过 α 粒子与子核的电荷密度积分给出。计算发现，由于非零角动量带来的禁戒效应和小的 α 粒子预形成几率，奇 Z 超重核的 α 衰变寿命会明显变长。

关键词： α衰变；超重核；结团模型

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