Alpha decay half-lives of odd-Z superheavy elements
Z=115→113→111

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Abstract. We present theoretical calculations on α-decay half-lives of the heaviest odd-Z elements 115→113→111 by the density-dependent cluster model. The microscopic 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 calculated α-decay half-lives with renewed Qα values are systematically compared with the experimental data.

1. Introduction
The synthesis of superheavy nuclei has received particular attention in nuclear physics in recent years [1]. Due to the fast development of modern accelerators and detectors under low temperature, many superheavy nuclei have been successfully synthesized at GSI, Dubna, RIKEN and Lawrence Berkeley National Laboratory of USA etc [2, 3, 4, 5, 6, 8, 7, 9, 10, 11, 12]. From the theoretical side, a number of works have also been performed to study the properties of even-Z superheavy elements. On the other hand, the progress on synthesis of odd-Z superheavy elements is relatively slower as compared with that of the even-Z superheavy elements. Very recently, the α-decay chains from the heaviest odd-Z element 115 and 113 have been successfully observed in experiments [9, 10, 13] and renewed experimental data are also reported in 2007 [14]. Such new experimental data provide a good opportunity to investigate the nuclear structure properties of these odd-Z superheavy nuclei.

Recently, we have proposed a new cluster model of α-decay (the density-dependent cluster model (DDCM)) where 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]. The exchange term is also introduced to the M3Y interaction in order 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 adjusted to reproduce the experimental α-decay energy by application of the 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, 18, 19].

The purpose of this work is to calculate the α-decay half-lives of the heaviest odd-Z elements 115→113→111 by the density-dependent cluster model. The renewed experimental α-decay
energies are used to calculate the half-lives in DDCM. The agreement between experimental and theory is discussed in detail. The outline of this paper is as follows. In section 2, we briefly introduce the framework of the density-dependent cluster model. The corresponding results and discussions are presented in section 3. A brief summary is given in the last section.

2. Framework of the density-dependent cluster model

In the density-dependent cluster model, the ground state of parent nucleus is assumed to be an $\alpha$-particle (or cluster) orbiting the daughter nucleus. The $\alpha$- (or cluster-) core potential is the sum of the nuclear potential, the Coulomb potential and the centrifugal potential [15]

$$V(R) = V_N(R) + V_C(R) + \frac{\hbar^2}{2\mu} \left( L + \frac{1}{2} \right)^2 \frac{1}{R^2} \tag{1}$$

where $V_N(R)$ and $V_C(R)$ 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 $\lambda$ in $V_N(R)$ is determined separately for each decay by applying the Bohr-Sommerfeld quantization condition [15]

$$V_N(R) = \lambda \int d\mathbf{r}_1 d\mathbf{r}_2 \rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2) g(E, |s|) \tag{2}$$

The mass density distribution of the spherical $\alpha$-particle $\rho_1$ is a standard Gaussian form given by Satchler and Love [20]. The mass density distribution of the daughter nucleus $\rho_2$ 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]

$$g(E, |s|) = 7999 \exp\left(-\frac{4s}{4s}\right) - 2134 \exp\left(-\frac{2.5s}{2.5s}\right) + J_{00} \delta(s), \tag{3}$$

$$J_{00} = -276(1 - 0.005 E_\alpha/A_\alpha) \tag{4}$$

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

$$V_C(R) = \int d\mathbf{r}_1 d\mathbf{r}_2 \frac{e^2}{|\mathbf{R} + \mathbf{r}_2 - \mathbf{r}_1|} \rho_1'(\mathbf{r}_1)\rho_2'(\mathbf{r}_2) \tag{5}$$

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

$$\Gamma = P_\alpha \frac{\hbar^2}{4\mu} \int_{R_1}^{R_2} dR \int_{R_1}^{R_2} dR' \frac{1}{K(R)} \cos^2\left(\int_{R_1}^{R} dR' K(R') - \frac{\pi}{4}\right) \tag{6}$$

Finally the $\alpha$-decay half-life is then related to the width by [15]

$$T_{1/2} = \frac{\hbar}{\ln 2}/\Gamma. \tag{7}$$
3. Numerical results and discussions

The detailed theoretical results of the α-decay energies and half-lives for the odd-Z superheavy elements are given in Table 1. In Table 1, the first column denotes the parent and daughter nuclei. The experimental α-decay energies are given in the second column. The third column is the preformation factors for the odd-Z and odd-odd superheavy nuclei. The global number G and the angular momentum L are given in the fourth column. The experimental and theoretical α-decay half-lives are listed in the last two column of Table 1, respectively.

One can see from Table 1 that the experimental α-decay energies vary from $Q_\alpha=9.938-11.737$ MeV. We note that the calculated α-decay half-lives are very sensitive to the decay energy and a change of 1.0 MeV in the $Q_\alpha$ value may result in a change of several orders of the magnitude of the α-decay half-lives. In present calculations, we still use the experimental decay energies in DDCM [15]. As mention above, the only free parameter in DDCM is the preformation factor of the α-particle in the parent nucleus. Here the values of $P_\alpha$ are taken from the global calculation for the heavy and superheavy nuclei [15]. For odd-Z 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]. Although the amplitude of the variation of the experimental α-decay half-lives is as high as $10^4$ times, we can see from Table I that the calculated lifetimes reasonably agree with the experimental ones. We can see that the half-lives of α-emitters $^{288}115$, $^{287}115$, $^{284}113$, $^{283}113$ are reproduced within a factor of 3. The deviation between experimental and calculated half-lives is a little large for other nuclides. It is unclear...
whether the assumption of favored transition is suitable for these nuclei. Therefore we assume that the angular momentum of the $\alpha$-particle is non-zero ($l = 3$ or $l = 5$). We can see from Table 1 that the agreement between experimental and calculated $\alpha$-decay half-lives is improved greatly by taking the angular momentum into account. Generally, the overall agreement is acceptable because the situation of odd-Z nuclei is rather complicated in superheavy mass region.

4. Summary
In summary, we have investigated the $\alpha$-decay half-lives of superheavy nuclei ($Z=115\rightarrow113\rightarrow111$) by the density-dependent cluster model. The theoretical $\alpha$-decay half-lives are calculated by using the renewed experimental $\alpha$-decay energies. The agreement between theory and experiment is generally reasonable for these odd-Z superheavy nuclei. The deviations between experimental and calculated half-lives is within a factor of 5 for most nuclei by taking into account the influence of the non-zero angular momentum.

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