Postprint of Theoretical Predictions for Decay Properties of 293, 294119 and 294, 295120 Superheavy Nuclei

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Abstract

Fusion-evaporation reactions ^{243Am}({54Cr},xn)^(297-x)119 and ^{243Am}({55Mn},xn)^(298-x)120 are potential routes recently proposed by nuclear physicists for synthesizing new elements with atomic numbers Z = 119 and 120. Alpha decay serves as a powerful tool for the experimental identification of newly synthesized elements or nuclides. Using the Improved Density-dependent Cluster Model (DDCM+), theoretical predictions have been made for the alpha-decay half-lives of the reaction products ^{293119}, ^{294119} and ^{294120}, ^{295120}, which are obtained from the fusion-evaporation reactions ^{243Am}({54Cr},xn)^(297-x)119 and ^{243Am}({55Mn},xn)^(298-x)120 through the evaporation of 3 or 4 neutrons. On this basis, the competition between alpha decay and other decay modes such as spontaneous fission and beta decay has been further analyzed for the nuclides ^{293119}, ^{294119} and ^{294120}, ^{295120}. The study reveals that alpha decay dominates for the majority of nuclei; however, along the alpha-decay chain, as the mass number decreases to approximately A = 261, the half-lives of spontaneous fission and beta decay become comparable to those of alpha decay. These theoretical results provide valuable reference for future work on synthesizing new elements with Z = 119 and 120.

Full Text

Predictions of the Decay Properties of the Superheavy Nuclei 293,294119 and 294,295120

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Abstract

[**Background**] To date, various nuclides up to Z = 118 have been discovered and synthesized, raising the challenge of synthesizing nuclides with Z = 119 and 120. Recently, the fusion-evaporation reactions ^{243}Am(^{54}Cr, xn)^{297119} and ^{243}Am(^{55}Mn, xn)^{298120} have been suggested as methods for synthesizing new elements with Z = 119 and 120. As α-decay is a powerful tool for the identification of new elements or nuclides, accurate predictions of the α-decay properties of the reaction products could be a useful reference for future experiments.
[**Purpose**] This study aims to provide quantitative predictions of the α-decay, spontaneous fission, and β-decay half-lives for the α-decay chains of 293,294119 and 294,295120 and to demonstrate the competition between the decay modes for these nuclei.
[**Methods**] An improved density-dependent cluster model (DDCM+) is used to calculate the α-decay half-lives, taking the anisotropy of the surface diffuseness into account. The spontaneous fission half-lives are calculated using the Karpov formula, which is related to the fissility parameter and fission barrier height of the potential energy surface. The β-decay half-lives are determined using a finite-range droplet model (FRDM).
[**Results**] The predictive α-decay half-lives for the α-decay chains of 293,294119 and 294,295120 are obtained using the DDCM+ model, and the theoretical half-lives of the spontaneous fission and β-decay for these nuclides are also presented.
[**Conclusions**] For the α-decay chains of 293,294119 and 294,295120, α-decay is predicted to be the dominant decay mode for most of the nuclei, while the half-lives of spontaneous fission and β-decay are predicted to be comparable to those of the α-decay near the region of A = 261. We expect that these results will serve as a useful reference for the synthesis of new isotopes in the future.

Key words α-decay, Spontaneous fission, Superheavy nuclei, Half-life

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1. Introduction

The synthesis and study of superheavy nuclei represent a hot topic in nuclear physics. Over the past half-century, with the successive construction of large heavy-ion accelerator facilities and continuous improvements in experimental detection techniques, nuclear physics laboratories worldwide have achieved a series of major breakthroughs in the synthesis of superheavy nuclei. For example, through the "cold fusion" reaction mechanism, the GSI Helmholtzzentrum für Schwerionenforschung in Germany first synthesized elements with Z = 107–112 [**?**]. Subsequently, using the "hot fusion" reaction, the Joint Institute for Nuclear Research in Dubna, Russia, further synthesized elements with Z = 112–118 [**?**, **?**]. Relying on the Heavy Ion Research Facility in Lanzhou (HIRFL), China has also made many contributions to superheavy nuclei synthesis, producing superheavy nuclides such as ^{259}Db and ^{265}Bh [**?**]. These experimental achievements have not only expanded the known range of nuclides but also greatly deepened our understanding of the structural properties of superheavy nuclei.

In recent years, experimentalists have begun attempting to synthesize new elements with Z > 118. One possible approach is to synthesize elements with Z = 119 and 120 through the fusion-evaporation reactions ^{243}Am(^{54}Cr, xn)^{297119} and ^{243}Am(^{55}Mn, xn)^{298120} [**?**]. However, due to limitations in equipment conditions and reaction mechanisms, successfully conducting relevant synthesis experiments remains challenging. α-decay is one of the important decay modes of superheavy nuclei and serves as a powerful tool for identifying new nuclides experimentally. Therefore, theoretical studies on the α-decay properties of superheavy nuclei provide important guidance for future synthesis experiments of new superheavy nuclides [**?**, **?**].

The density-dependent cluster model (DDCM) is one of the more successful models for studying α-decay. This model considers the density distribution of atomic nuclei and the low-density behavior of nucleon-nucleon interactions, and it can provide reasonable descriptions of the α-decay properties for most nuclides in the region of Z = 52 [**?**, **?**]. Recently, we have further considered the effect of nuclear deformation on the surface diffuseness of nucleons. Based on the original DDCM model, we introduced deformation-dependent diffuseness parameters and proposed the improved density-dependent cluster model (DDCM+) [**?**, **?**], which further enhances the precision of theoretical calculations. In this paper, we systematically calculate the α-decay properties of the unknown nuclides 293,294119 and 294,295120 using the DDCM+ model, and simultaneously analyze the competition between different decay modes such as α-decay, spontaneous fission, and β-decay for these nuclides to provide a reference for future related experiments.

1.1 Improved Density-Dependent Cluster Model (DDCM+)

In the DDCM+ model, the parent nucleus is considered as a two-body system composed of a spherical α-cluster and an axially symmetric deformed daughter nucleus. The interaction between the α-cluster and the daughter nucleus can be expressed as:

$$V(r,\xi) = V_N(r,\xi) + V_C(r,\xi) + \frac{\hbar^2 L(L+1)}{2\mu r^2}$$

where r represents the distance between the α-particle and the center of mass of the daughter nucleus; $V_N(r,\xi)$ represents the nuclear potential; $V_C(r,\xi)$ represents the Coulomb potential; L denotes the angular momentum carried by the α-particle (in this work, since the energy level information of the predicted nuclides is unknown, L is taken as 0); μ represents the reduced mass of the α-particle and daughter nucleus; and ξ represents the angle between the α-particle emission direction and the symmetry axis of the daughter nucleus. Both the nuclear and Coulomb potentials are given by microscopic double-folding potentials [**?**]:

$$V_N(r,\xi) = \lambda \int \rho_{p,c}(\mathbf{r}_c) + \rho_{n,c}(\mathbf{r}_c) \times \nu(s = |\mathbf{r}_c + \mathbf{r}_\alpha|) \times [\rho_{p,\alpha}(\mathbf{r}_\alpha) + \rho_{n,\alpha}(\mathbf{r}_\alpha)] d\mathbf{r}_c d\mathbf{r}_\alpha$$

$$V_C(r,\xi) = \frac{e^2}{4\pi\varepsilon_0} \int \frac{\rho_{p,c}(\mathbf{r}_c)\rho_{p,\alpha}(\mathbf{r}_\alpha)}{|\mathbf{r}_c + \mathbf{r}_\alpha|} d\mathbf{r}_c d\mathbf{r}_\alpha$$

where λ is a normalization factor determined by solving the quasi-bound state Schrödinger equation such that the corresponding eigenenergy equals the α-decay energy Q_α; $\rho^\alpha_{p,n}(\mathbf{r}_\alpha)$ and $\rho^c_{p,n}(\mathbf{r}_c)$ represent the nucleon density distributions of the α-particle and daughter nucleus, respectively (superscript p denotes protons, n denotes neutrons). The nucleon density in the α-particle, $\rho^\alpha_\tau(\mathbf{r}_\alpha)$, is typically taken as a standard Gaussian distribution, while the nucleon density distribution of the daughter nucleus, $\rho^c_\tau(\mathbf{r}_c)$, is usually taken as a Fermi-type distribution, as shown in equations (4) and (5):

$$\rho^\alpha_\tau(\mathbf{r}_\alpha) = \rho^\alpha_{\tau 0} \exp\left(-0.702 \frac{4|\mathbf{r}_\alpha|^2}{a_\tau^2}\right)$$

$$\rho^c_\tau(\mathbf{r}_c) = \frac{\rho^c_{\tau 0}}{1 + \exp\left(\frac{|\mathbf{r}_c| - R_\tau(\theta)}{a_\tau(\theta)}\right)}$$

where the central nucleon densities $\rho^\alpha_{\tau 0}$ and $\rho^c_{\tau 0}$ can be determined by integrating the nucleon density distribution functions over all space such that the integral equals the corresponding nucleon number. The radius parameter $R_\tau(\theta)$ is expressed as:

$$R_\tau(\theta) = R_\tau \left[1 + \sum_{i=2,4,6} \beta_i Y_{i0}(\theta)\right]$$

where $\beta_i (i = 2, 4, 6)$ are deformation parameters whose values are taken from Ref. [**?**]. The diffuseness parameter $a_\tau(\theta)$ is given by:

$$a_\tau(\theta) = a_\tau \left[1 + \sum_{i=2,4,6} \frac{R_\tau(\theta)}{R_\tau} \frac{dR_\tau(\theta)}{d\theta}\right]$$

The specific form can be found in Refs. [**?**, **?**]. The nucleon-nucleon interaction $\nu(s)$ in the nuclear potential adopts the M3Y-Reid effective nucleon-nucleon interaction [**?**]:

$$\nu(s) = 7999.00 \frac{\exp(-4s)}{4s} - 2134.00 \frac{\exp(-2.5s)}{2.5s} + 0.005(E_\alpha/A_\alpha)\delta(s)$$

where E_α/A_α represents the average kinetic energy per nucleon in the emitted α-particle.

For deformed nuclei, the total α-decay width can be obtained by averaging the decay widths over different orientation angles ξ. In the DDCM+ model, the α-decay width at a certain orientation angle ξ is expressed as [?]:

$$\Gamma(\xi) = \frac{2}{\hbar}\int_{r_2}^{r_3} \frac{|\phi_L(r,\xi)|^2}{\sqrt{\frac{2\mu}{Q_\alpha}\left[V_N(r,\xi)+V_C(r,\xi)+\frac{\hbar^2 L(L+1)}{2\mu r^2}-Q_\alpha\right]}}dr$$

where $F_L(kr)$ is the regular Coulomb wave function; $k = \sqrt{2\mu Q_\alpha}/\hbar$ is the wave number; and $\phi_L(r,\xi)$ represents the radial wave function corresponding to orientation angle ξ. The number of internal nodes N of the radial wave function $\phi_L(r,\xi)$ is approximately determined by the Wildermuth-Tang condition [?]:

$$G = 2N + L$$

where G represents the total quantum number. Due to the Pauli blocking effect, G is taken as 22 in this work. After obtaining the α-decay widths in all directions, the total α-decay width is given by:

$$\Gamma = \frac{1}{2}\int_0^\pi \Gamma(\xi)\sin\xi d\xi$$

Finally, the α-decay half-life can be expressed as:

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

where P_α is the preformation factor, which measures the preformation probability of the α-cluster inside the parent nucleus. Studies have shown that in regions far from closed shells, the value of P_α varies slowly [?]. Therefore, to reduce the number of free parameters in the model, P_α is taken as a constant in this work. For even-even nuclei, P_α is taken as 0.1521 [?], while for odd-A and odd-odd nuclei, P_α is taken as 0.0926 and 0.0712, respectively [?].

1.2 Karpov Formula

Spontaneous fission is another important decay mode of superheavy nuclei, and theoretical studies of spontaneous fission are also significant for understanding the stability properties of superheavy nuclei. Compared with α-decay, the mechanism of spontaneous fission is more complex, and there is also great uncertainty in the fission process. In previous works, several theoretical methods have been proposed to calculate spontaneous fission half-lives, such as those in

Refs. [?, ?]. In this paper, we use the Karpov formula to predict the spontaneous fission half-lives of relevant nuclides [?], which has the following specific form:

$$\log_{10}(T_{SF}^{1/2}) = 1146.44 + 1.63792(0.0119827\frac{Z^2}{A} - B_f) + \begin{cases} 1.53897, & \text{even-even nuclei} \\ 0.80822, & \text{odd-A nuclei} \\ 0.0, & \text{odd-odd nuclei} \end{cases}$$

where B_f represents the fission barrier height, with specific values taken from Ref. [?]. The Karpov formula combines the fission parameter with the fission barrier height of the potential energy surface and can well reproduce the spontaneous fission behavior of heavy and superheavy nuclei [?, ?].

2. Results and Discussion

Using the DDCM+ model, we have predicted the α-decay half-lives of 293,294119 and 294,295120 and the nuclides in their α-decay chains. Since the α-decay half-life is strongly sensitive to the α-decay energy, we adopt two sets of α-decay energies in this work: those from the α-decay energy formula in Ref. [?] and those from the Finite-range Droplet Model (FRDM) [?]. The relevant calculation results are listed in Table 1 , where Q_α^{th1} and Q_α^{th2} represent the α-decay energies from Ref. [?] and the FRDM model, respectively; T_α^{th1} and T_α^{th2} represent the results calculated using the DDCM+ model combined with Q_α^{th1} and Q_α^{th2}, respectively; T_{SF} represents the spontaneous fission half-life predicted using the Karpov formula. Möller et al. [?] also provided predictions for α-decay and β-decay energies and β-decay half-lives using the FRDM model. As a comparison, these predicted results are also listed in Table 1, denoted as T_α^{th3}, Q_β, and T_β, respectively. It is worth noting that Table 1 presents two different sets of α-decay energy data from Q_α^{th1} and Q_α^{th2}.

As can be seen from Table 1, due to the dependence and sensitivity of the theoretical model on α-decay energy, the DDCM+ model gives two different half-lives corresponding to these two different α-decay energies. For the same nuclide, a change of 1 MeV in α-decay energy results in approximately three orders of magnitude change in the α-decay half-life predicted by the DDCM+ model. Therefore, developing accurate α-decay energy (or mass) models is crucial for predicting the α-decay half-lives of unknown nuclides in the future. Furthermore, Table 1 shows that the predicted α-decay half-lives for 293,294119 and 294,295120 and the nuclides in their α-decay chains range from 10^{-7} to 10^{6} s, which can be precisely measured by existing experimental techniques. Therefore, α-decay can still serve as an excellent identification tool for these new nuclides in future synthesis experiments.

To more intuitively analyze the competition between different decay modes such as α-decay, spontaneous fission, and β-decay for 293,294119 and 294,295120 and the nuclides in their α-decay chains, the half-lives of different decay modes along these decay chains are shown in Figure 1 [Figure 1: see original paper].

As can be seen from Figure 1, along the same α-decay chain, T_α^{th2} and T_α^{th3} show the same trend and relatively close results, while T_α^{th1} exhibits a different trend. This is because T_α^{th1} uses different α-decay energies from T_α^{th2} and T_α^{th3}. This difference in trends again demonstrates the necessity of developing accurate α-decay energy (or mass) models for predicting α-decay half-lives. By comparing the half-lives of α-decay, spontaneous fission, and β-decay along the four decay chains, we find that for the new nuclides 293,294119 and 295120, the α-decay mode is dominant, while spontaneous fission and β-decay are relatively more stable and have similar half-lives. In contrast, for the new nuclide 294120, although α-decay is still dominant, its spontaneous fission half-life is closer to its α-decay half-life compared with 293,294119 and 295120. Along the α-decay chains, as the mass number of the daughter nucleus decreases, the branching ratio of the α-decay mode gradually decreases, and its half-life gradually approaches those of the other two decay modes. Even for the nuclides 261,262Lr in the α-decay chains of 293,294119, β-decay has become relatively dominant. Therefore, for nuclides with A   261 in these decay chains, other decay products need to be considered carefully in experimental identification.

3. Conclusion

In this work, we have used the improved density-dependent cluster model combined with two different sets of predicted α-decay energies to predict the α-decay half-lives of 293,294119 and 294,295120 and the nuclides in their α-decay chains, and have discussed the competition between different decay modes such as α-decay, spontaneous fission, and β-decay for these nuclides. Our analysis shows that for the unknown nuclides 293,294119 and 294,295120, α-decay is the main decay mode. However, along the α-decay chains, as the mass number gradually decreases, the branching ratio of the α-decay mode gradually decreases, and its half-life gradually approaches those of spontaneous fission and β-decay. We hope that these predictions will provide a useful reference for future synthesis experiments of new nuclides.

Author Contributions: WANG Zhen was responsible for computational program design, data analysis, and manuscript writing; REN Zhongzhou was responsible for paper guidance, review and revision, and research project funding support.

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Note: Figure translations are in progress. See original paper for figures.