

Systematics of Alpha-Decay Half-Lives in Plutonium Isotopes

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Introduction

Alpha decay is a dominant decay mode in heavy and superheavy nuclei, providing crucial insights into nuclear stability and structure [1, 2]. In the actinide region, particularly Plutonium (Pu), systematic studies of alpha-decay half-lives shed light on shell evolution, deformation, and barrier dynamics. The decay process is highly sensitive to Q_α values, shell closures, and collective effects, making it an important probe for nuclear structure study. In the present work, we investigate Pu isotopes in the range $A = 220$ – 244 using the Preformed Cluster-decay Model (PCM) [3] with the Proximity 1988 nuclear potential and the Wentzel–Kramers–Brillouin (WKB) approximation for barrier penetration. The neck-length parameter is optimized to improve predictive accuracy. This framework allows extraction of key decay parameters such as preformation probability, penetration probability, and barrier characteristics, which are then compared with experimental systematics and extended to unexplored isotopes. The results highlight the strong influence of shell closures and deformation on alpha-decay lifetimes, with enhanced stability signatures observed at both spherical ($N = 126$) and deformed ($N = 128, 134, 144$) neutron numbers. Predictions for several yet-unconfirmed isotopes identify promising candidates for future experimental observation. This study provides a unified understanding of alpha-decay behavior in plutonium isotopes and contributes to applications in nuclear structure,

reactor physics, and nucleosynthesis modeling.

Theoretical Formalism

The alpha-decay constant is expressed as $\lambda = P_0 \nu P$, where P_0 is the preformation probability, ν the assault frequency, and P the tunneling probability. The latter is evaluated within the WKB approximation:

$$P = \exp \left[-\frac{2}{\hbar} \int_{r_a}^{r_b} \sqrt{2\mu(V(r) - Q_\alpha)} dr \right],$$

with r_a and r_b the classical turning points. The interaction potential is modeled as

$$V(r) = V_N(r) + V_C(r) + V_\ell(r),$$

where $V_N(r)$ is described by the Prox 1988 nuclear potential, $V_C(r)$ the Coulomb term, and $V_\ell(r)$ the centrifugal contribution. Deformation effects are included through multipole expansions, and the neck-length parameter is optimized to minimize deviations from experimental half-lives. The half-life is obtained as $T_{1/2} = \ln(2)/\lambda$.

Result and Discussions

The reliability of the Preformed Cluster-decay Model (PCM) approach was first verified by comparing its predictions with experimentally known alpha emitters across actinide and neighboring chains. In this study, nuclear deformations up to the quadrupole term (β_2) [4] have been incorporated, with optimum cold orientations adopted from Table 1 of Ref. [5]. The Q -values used in the calculations are taken from the mass evaluations of Möller and Nix [4], expressed as a function of the parent mass number A . The calculated half-lives are shown in Fig. 1. Excellent agreement is obtained for a wide set of isotopes, including ^{220–230,236,238–240,242,244}Pu,

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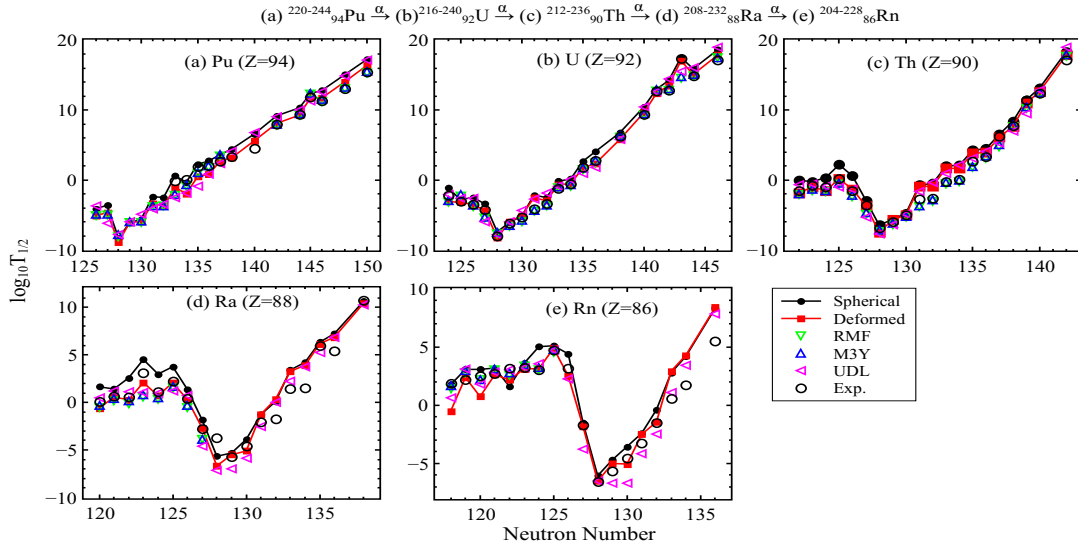


FIG. 1: (Color online) Comparison of calculated and experimental α -decay half-lives ($\log_{10} T_{1/2}$) as a function of neutron number for decay chains of (a) Pu ($Z = 94$, $A = 220-244$), (b) U ($Z = 92$, $A = 216-240$), (c) Th ($Z = 90$, $A = 212-236$), (d) Ra ($Z = 88$, $A = 208-232$), and (e) Rn ($Z = 86$, $A = 204-228$). Results are shown for spherical (black circles) and deformed (red squares) shapes, together with predictions from RMF (green triangles) [1], M3Y (blue triangles) [1], and UDL (magenta triangles) [2]. Experimental data [6] are denoted by open black circles.

216–219, 221–228, 230, 232, 233, 235, 236, 238 U, 212–230, 232 Th, 209–211, 214–224, 226 Ra, and 210, 212–220, 222 Rn, confirming the robustness of the model. Beyond the established emitters, our calculations extend to isotopes without experimental confirmation, predicting strong alpha-decay candidates such as $^{231,232,234}\text{Pu}$, $^{220,234}\text{U}$, $^{208,212}\text{Ra}$, and $^{204-209,211}\text{Rn}$, while isotopes like $^{233,235,237,241,243}\text{Pu}$, $^{229,231,237,239,240}\text{U}$, $^{231,233-236}\text{Th}$, $^{213,225,227-232}\text{Ra}$, and $^{221,223-228}\text{Rn}$ exhibit significant hindrance due to unfavorable barrier or structural effects. This enhancement around $N = 128$ suggests that the shell closure at $N = 126$ stabilizes the daughter nucleus, increasing the likelihood of alpha preformation and tunneling. It reflects the strong influence of shell effects on decay dynamics near magic numbers. Alongside the well-known spherical closure at $N = 126$, our study identifies emerging stability signatures at $N = 134$ and $N = 144$ in Pu isotopes, at $N = 144$ in U, $N = 124$ in Ra, and $N = 122$ in Rn, pointing to the role of deformed shell

closures. Furthermore, Plutonium isotopes display considerable deformation, which alters barrier height and position, thereby affecting half-life predictions an effect more prominent in Pu compared to lighter actinides. Finally, standard deviation analysis between calculated and known half-lives demonstrates quantitative agreement with experimental data, validating the predictive power of the PCM framework.

References

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