Competition between alpha decay and spontaneous fission for isotopes of plutonium

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Abstract. In the present work, a systematic study of various decay modes, namely α-decay, $\beta^{\pm}$-decay, electron capture (EC), and spontaneous fission (SF), has been carried out for plutonium (Pu) isotopes in the mass region $212 \leq A \leq 260$. The α-decay half-lives were evaluated using the modified generalized liquid drop model (MGLDM), while the β-decay and SF half-lives were estimated using well-established semi-empirical formulas. The calculated Q-values for α-decay range from 9.17 MeV to 2.57 MeV, indicating energetically allowed transitions in this region. The results show that α-decay dominates in isotopes $^{212-230}$Pu, ^{236}Pu, $^{238-240}$Pu, ^{242}Pu, and ^{244}Pu with logarithmic half-lives between −5.91 and 16.59. The β^{+}-decay mode is favored in ^{231}Pu, ^{233}Pu, and ^{235}Pu, whereas EC is dominant in ^{232}Pu, ^{234}Pu, and ^{237}Pu. For heavier isotopes ($A \geq 241$), β^{-}-decay becomes the most probable decay mode. The calculated standard deviations are found to be 0.975 for α-decay, 1.117 for β^{-}-decay, 3.189 for β^{+}-decay, and 0.908 for EC, indicating good agreement with experimental data. Furthermore, about 16 new α emitters and 13 new β^{-} emitters are predicted, which may guide future experimental investigations.

1 Introduction

Groundbreaking studies on various spontaneous ground-state decays have played a crucial role in advancing our understanding of nuclear structure and properties. The discovery of alpha (α) radioactivity was a foundational moment in early nuclear physics and remains a dominating decay mode for heavy and superheavy nuclei. Approximately four decades later, in 1939, the discovery of nuclear fission revealed a new process in which a highly unstable nucleus divides into two nearly equal fragments [1, 2]. This spontaneous fission (SF) is energetically feasible for heavy and superheavy nuclei with proton number Z>90. In 1980, about forty years after fission's discovery, it was theoretically proposed that unstable nuclei could also decay via a unique and exotic process called cluster radioactivity [3, 4]. Unlike the classical modes, cluster radioactivity involves the emission of a fragment heavier than an alpha particle, offering new perspectives on nuclear stability and enriching our

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understanding of nuclear decay mechanisms. Additionally, the authors of [5, 6] investigated the phenomenon of heavy particle radioactivity (HPR) in superheavy elements (SHEs), characterized by the spontaneous release of heavy clusters from the parent nucleus.

Theoretically, both α-decay and SF are governed by the same fundamental mechanism: quantum tunneling. Extensive studies have been conducted to calculate the half-lives of α-emitting nuclei across the entire nuclide chart, including those in the superheavy mass region [7–17]. In α decay, the process is typically described as a α cluster forming within the parent nucleus and then tunneling through the Coulomb barrier. The absolute decay width is primarily determined by the product of the cluster formation probability and its barrier penetration probability. [18] studied detailed investigations on SF half-lives and specific fission rates of ^{238}Pu, ^{240}Pu, and ^{242}Pu isotopes. ^{192}Os(^{40}Ar, 5n)^{227}Pu reaction and identified by decay correlations [19]. Its decay energy α and half-life of 8191(28) keV and $0.78^{+0.39}_{-0.19}$ s were measured, respectively, indicating a delayed α transition with angular momentum change ΔL = 2. The energy and yield of Long Range Alpha (LRA) particles from SF of ^{238,240,240,242,244}Pu were measured [20], revealing that LRA emission strongly depends on α-cluster preformation probability. The half-lives of partial alpha decay of^{242}Pu and ^{244}Pu were measured [21] using a relative specific activity method using ^{239}Pu as a reference, yielding values of 3.869×10^5 and 8.28×10^7 years, respectively. For ^{244}Pu, alpha particle energies to the ground and first excited states of ^{240}U were 4.587 MeV and 4.544 MeV. The α-decay Q-value of ^{244}Pu has been precisely measured as 4.701 ± 0.001 MeV. Building on the collective clusterization approach, [22] investigated α-decay, heavy particle radioactivity, and exotic cluster decay to include the study of SF in the ground-state decays of even-mass $^{234-246}$Pu isotopes. Earlier studies [15, 23, 24] investigated the decay times of isotopes of Pu nuclei.

The study of nuclear decay modes such as α-decay, SF, and exotic cluster radioactivity has been pivotal in advancing our understanding of nuclear structure, especially in heavy and superheavy nuclei. Among these, plutonium (Pu) isotopes occupy a unique position due to their rich decay characteristics and practical relevance in nuclear science and technology. Recent studies have highlighted the critical role of Pu isotopes in the synthesis of SHEs like Z = 114 [25, 26, 26, 27], which extends the boundaries of the periodic table. Accurate predictions of α-decay and SF half-lives, along with decay energies, are crucial for identifying and characterizing these new elements. Given these scientific and practical implications, we are motivated to carry out a detailed analysis of α-decay and SF half-lives across Pu isotopes. Using the modified liquid drop model for α-decay and established semi-empirical formulas for SF, our goal is to systematically evaluate these decay modes and contribute to a more comprehensive understanding of nuclear decay behavior in plutonium isotopes.

2 Theoretical framework

2.1 Alpha-decay half-lives

In the MGLDM, or the Modified Generalized Liquid Drop Model [28, 29], the total amount of potential energy associated with α-decay is represented as the sum of several contributing terms: the volume energy E_V, surface energy E_S, Coulomb energy E_C, proximity energy E_P, and the centrifugal energy E_ℓ. Mathematically, it is expressed as:

$$E = E_v + E_s + E_c + E_P + E_\ell \tag{1}$$

The total potential is calculated as explained in the literature [30]. For the deformed nuclei the volume (E_V), surface (E_s) and coulomb energies (E_c) are given by;

$$E_v = -15.494(1 - 1.8I^2)A \;\; MeV \tag{2}$$

$$E_s = 17.9439(1 - 2.6I^2)A^{2/3}\frac{S}{4\pi R_0^2} \;\; MeV \tag{3}$$

$$E_c = 0.6e^2(Z^2/R_0) \times 0.5 \int (V(\theta)/V_0) (R(\theta)/R_0)^3 sin(\theta)d\theta \;\; MeV \tag{4}$$

Where I and S are the relative neutron excess and surface area of the deformed nucleus, respectively. V(θ) and V_0 represent the electrostatic potential and surface potential of the sphere, respectively. When the nuclei are far apart, the equations are expressed as follows:

$$E_v = -15.494(1 - 1.8I_1^2)A_1 + (1 - 1.8I_2^2)A_2 \;\; MeV \tag{5}$$

$$E_s = 17.9439(1 - 2.6I_1^2)A_1^{2/3} + (1 - 2.6I_2^2)A_2^{2/3} \;\; MeV \tag{6}$$

$$E_c = 0.6e^2(Z_1^2/R_1) + 0.6e^2(Z_2^2/R_2) + e^2 Z_1 Z_2/r \;\; MeV \tag{7}$$

A_i, Z_i, R_i, and I_i are represented by the standard notations for mass number, atomic number, radii of the two nuclei, and relative neutron excess of the two nuclei, respectively. Furthermore, I_2=0, implying that E_V and E_S have negative and positive values. Additionally, the term E_ℓ is expressed as:

$$E_l(r) = \frac{\hbar^2}{2\mu}\frac{\ell(\ell+1)}{r^2} \tag{8}$$

where μ, r, and ℓ are the reduced mass, distance between the mass centers, and angular momentum, respectively. The nuclear proximity potential [31] is given by;

$$E_P = 4\pi\gamma\bar{R}\Phi(S_0) \tag{9}$$

here $\bar{R}$ is the mean curvature radius, and it is given by $\bar{R} = \frac{C_1 C_2}{C_1 + C_2}$ the Sussmann central radii C_i is calculated as follows:

$$C_i = R_i - \left(\frac{b^2}{R_i}\right) \tag{10}$$

Sharp radii R_i is expressed as;

$$R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3} \tag{11}$$

The equation (9) defines γ as

$$\gamma = \gamma_0\left[1 - I_s\left(\frac{N-Z}{A}\right)^2\right] MeV/fm^2 \tag{12}$$

where γ_0= 1.460734 MeV/fm^2 and I_s= 4.0, and the various universal proximity functions in equation 9 are evaluated using the double-folding model (DFM) with the density-dependent nucleon-nucleon interaction. Zhang et al., [32] studied the universal function, and it is expressed as;

$$\phi(S_0) = \frac{P_1}{1 + exp\left(\frac{S_0+P_2}{P_3}\right)} \tag{13}$$

with $S_0 = \frac{R-R_1-R_2}{b}$ and P_1, P_2, and P_3 are the constants whose values are -7.65, 1.02, and 0.89, respectively [32]. The penetration probability using WKB integration:

$$P = exp\left[-\frac{2}{\hbar}\int_{R_{in}}^{R_{out}} \sqrt{2B(r)E(r) - E(sphere)}\right] \tag{14}$$

here R_{in} and R_{out} are the classical turning points with the conditions $V(r = R_{in}) = V(r = R_{out}) = Q$. μ represents the cluster and daughter nuclei's reduced mass. The half-lives of cluster emission from the odd superheavy nuclei in the atomic number range $105 \leq Z \leq 125$ were evaluated with the following equation:

$$T_{1/2} = \left(\frac{ln2}{\lambda}\right) = \left(\frac{ln2}{\nu P}\right) \tag{15}$$

here decay constant λ depends on the frequency of assaults. $\nu = \left(\frac{\omega}{2\pi}\right) = \left(\frac{2E_\nu}{h}\right)$. Here E_ν is the Zero-point empirical vibrational energy and it is expressed as;

$$E_v = Q\left[0.056 + 0.039exp\left(\frac{4-A_e}{2.5}\right)\right] \ MeV \tag{16}$$

Here A_e represents the mass number of the emitted cluster particle. The term P in equation (15) is the penetration probability of cluster decay.

2.2 Spontaneous fission half-lives

The SF half-lives were evaluated using the following empirical formula [33];

$$T_{1/2}(yr) = c_1 + c_2\left(\frac{Z^2}{(1-kI^2)A}\right) + c_3\left(\frac{Z^2}{(1-kI^2)A}\right)^2 + c_4E_{sh} + h_i \tag{17}$$

where, c_1 = 1174.353441, $c_2 = -47.666855$, $c_3 = 0.471307$, and $C_4 = 3.378848$. $k = 2.6$ and h_i is the blocking effect. Further, the term $\frac{Z^2}{(1-kI^2)A}$ denotes the fissionability parameter when isospin effect has been included.

2.3 Beta-decay

The β^- decay mainly occurs in neutron-rich nuclei, whereas β^+ decay and EC predominantly take place in proton-rich nuclei. The comprehensive formulas for determining the half-lives of these modes of beta decay are given in Ref.[34] and are as follows:

$$\log T_{1/2} = a_Z Z + a_A A + a_Q Q^{-1/4} + a_I I + a \tag{18}$$

where the mass and atomic numbers of the parent nucleus are denoted by A and Z respectively, Q is the decay energy (in MeV), and $I = (N - Z)/A$ is the isospin asymmetry parameter. The coefficients a_Z, a_A, a_Q, a_I, and a are fitting parameters derived from data from experiments and are provided in Reference [34].

3 Results and Discussions

Q-values indicate the quantity of energy released or absorbed during a nuclear reaction and form the foundation for understanding the energetics of nuclear processes. They are essential for determining whether a given reaction is energetically favorable, which is crucial when studying nuclear stability and decay mechanisms. In this work, various decay modes—including α-decay, β-decay, and SF were examined in isotopes of plutonium with mass numbers ranging from $212 \leq A \leq 290$, using the theoretical framework described in the theory section. In particular, the modified generalized liquid drop model (MGLDM) incorporates proximity, shell, and pairing effects, providing a realistic description of nuclear structure. It improves predictions of αdecay, cluster decay, and fission. The model is especially useful for studying heavy and superheavy nuclei, guiding experiments and understanding nuclear stability and reaction mechanisms. A key parameter in analyzing these decay processes is the Q-value, which quantifies the decay energy released. It is calculated as follows;

$$Q = \Delta M(A, Z) - \Delta M_d(A_d, Z_d) - \Delta M_e(A_e, Z_e) \tag{19}$$

Here, $\Delta M(A, Z)$, $\Delta M_d(A_d, Z_d)$ and $\Delta M_e(A_e, Z_e)$ represent the mass excesses of the parent, daughter, and emitted nuclei (such as α, β-decay), respectively. The decay energies corresponding to various decay modes were investigated for $^{212-290}$Pu isotopes.These energies were computed using the mass excess values reported in the literature [35]. These mass excess values are utilized in the evaluation of half-lives. A small change in the mass excess results in the magnitude of an order of difference in the prediction of half-lives. Therefore, the accuracy of half-life predictions is inherently linked to the uncertainties in the mass excess values. [35] employed a least-squares adjustment along with a maximum-likelihood statistical method to determine the intrinsic model error (σ_{th}) of the finite-range droplet model (FRDM) as 0.669 MeV.

Figure 1 illustrates the variation of decay energy (Q-value) with the mass number of different isotopesof plutonium (Pu), highlighting the energetically allowed decay modes. For α-decay, isotopes ranging from ^{212}Pu to ^{260}Pu show positive Q-values between 9.165 MeV and 2.575 MeV, indicating feasible decay. In the case of β^+-decay, isotopes such as $^{212-231}$Pu, ^{233}Pu, and ^{235}Pu exhibit positive Q-values from 7.348 MeV to 0.117 MeV, while isotopes heavier than ^{235}Pu have negative Q-values, indicating the suppression of this decay channel. For β^--decay, positive Q-values are observed in isotopes from ^{245}Pu to ^{243}Pu, including ^{241}Pu and ^{243}Pu, with decay energies ranging from 0.4 MeV to 5.58 MeV, making them energetically favorable. Additionally, electron capture is allowed in the isotopes ^{212}Pu to ^{234}Pu, and ^{237}Pu, with decay energies between 9.81 MeV to 0.22 MeV. These results suggest distinct regions in the Pu isotopic chain where different decay modes dominate, aiding in the identification of decay pathways and nuclear stability trends among plutonium isotopes.

The applicability of α-decay half-lives in plutonium isotopes has been assessed by comparing the outcomes of the present study with those data from experiments [36] and well-established semi-empirical formulas such as UNIV [37], NRDX [38], UDL [39], SAHU [40], and Horoi [41]. Figure 2 illustrates this comparison, showing the logarithmic α-decay half-lives as a function of mass number (A) for Pu isotopes. The observed trend reveals that the half-life initially rises as the mass number increases initially increases with increasing mass number, reaches a peak, and then decreases again. Specifically, isotopes from ^{212}Pu to ^{245}Pu exhibit relatively short half-lives, indicating a higher probability of α-decay and rapid decay behavior. From ^{245}Pu to ^{260}Pu, the half-lives rise and reach a peak, suggesting these nuclei are comparatively more stable against α-decay. In addition, we observed two pronounced maxima in figure 2 for parent mass numbers ≈247 and 256 are attributable to

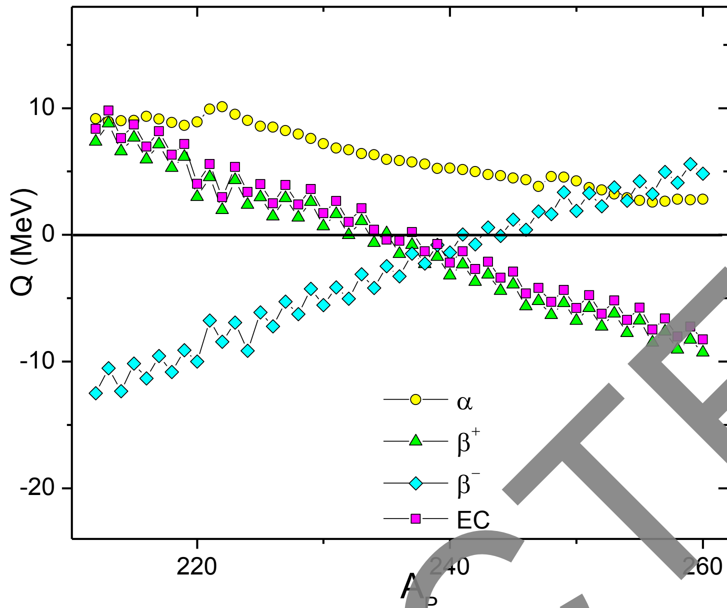

Figure 1. A plot of decay energies of α, β^{+}, β^{-}, and electron capture as a function of mass number of parent nuclei in the isotopes of Pu.

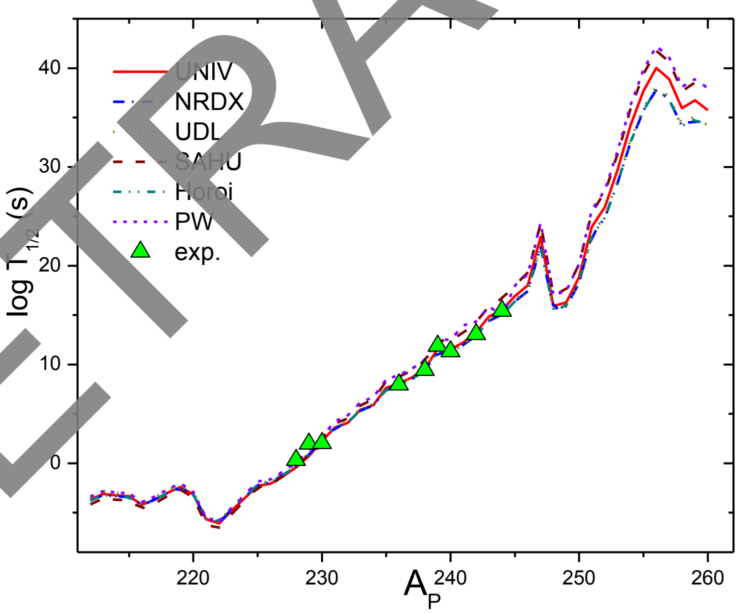

Figure 2. A comparison of α-decay half-lives in the isotopes of Pu nuclei with those of experiments [36], and semi-empirical formula available in literature such as UNIV [37], NRDX [38], UDL [39], SAHU [40], and Horoi [41].

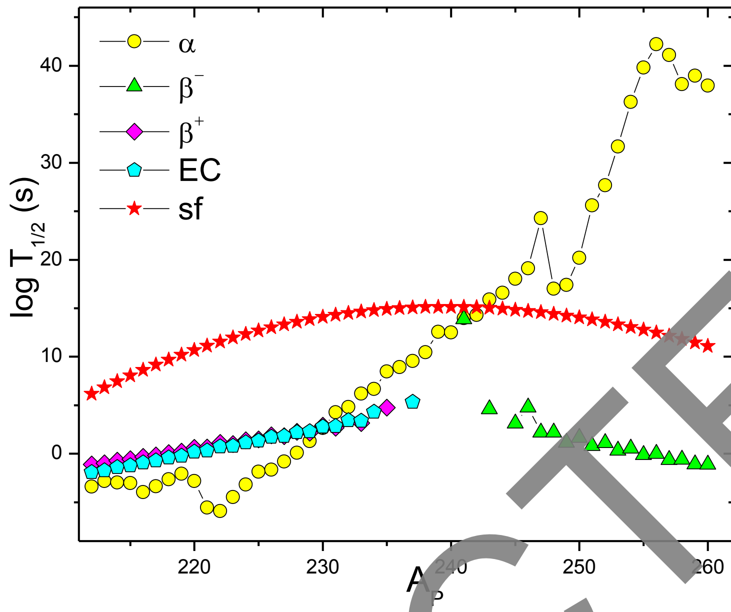

Figure 3. A plot of logarithmic half-lives of α-decay, $\beta^{\pm}$-decay, electron capture, and SF as a function of mass number of parent nuclei in the isotopes of Pu nuclei.

nuclear-structure stabilization of the corresponding daughter nuclei. As the parent mass increases the decay channels increasingly populate daughters that approach known shell gaps (notably the deformed N≈154 region and the predicted spherical N≈162 closure). These shell effects increase daughter binding energy and reduce alpha preformation/penetrability, producing strong hindrance and hence local maxima in $\log T_{1/2}$. The lower mass region (A = 212–240) exhibits comparatively smoother behavior since the corresponding daughter nuclei lie farther from the stabilizing shell closures, resulting in reduced Coulomb hindrance.

In addition to studying α-decay and β-decay, we also analyzed the SF half-lives of Pu isotopes. The logarithmic half-lives corresponding to various decay modes were calculated and presented in Figure 3. The study focuses on isotopes within the mass number range $212 \le A \le 260$, where the expected half-lives are within the detectable range. Among these, the α-decay mode is found to dominate in several isotopes, particularly $^{212-230}$Pu, ^{236}Pu, $^{238-240}$Pu, ^{242}Pu, and ^{244}Pu, due to their relatively shorter half-lives compared to other decay channels. This suggests that the isotopes are more likely to undergo α-decay. The isotopes ^{231}Pu, ^{233}Pu and ^{235}Pu exhibit shorter half-lives for β^+-decay, making this the preferred decay mode. Likewise, electron capture is dominant in ^{232}Pu, ^{234}Pu, and ^{237}Pu, as indicated by their lower half-lives. In contrast, β^--decay is favored in heavier isotopes, specifically ^{241}Pu, ^{243}Pu, and $^{245-260}$Pu, where it exhibits the lowest half-lives among all decay modes. These observations help identify the most probable decay pathways and provide insight into the stability and transformation mechanisms of Pu isotopes across a wide mass range.

Furthermore, Table 1 presents a detailed comparison between the present theoretical predictions and the accessible experimental data for a variety of plutonium isotopes, emphasizing decay modes such as α, $\beta^{\pm}$, and electron capture (EC). The theoretical results include the calculated Q-values and corresponding $logT_{1/2}$ for each possible decay channel, while the experimental values are obtained from the reference [36]. For lighter plutonium isotopes

Table 1. A comparison of the logarithmic half-lives for various decay modes, highlighting the dominant theoretically predicted mode, with corresponding experimental values and observed decay modes for plutonium isotopes.

PN	Theoritical log $T_{1/2}$(s)								Exp.[36]	
	Q (MeV)	α	β^-	β^+	EC	SF	log$T_{1/2}$ (s)	Decay Mode	log$T_{1/2}$ (s)	Decay Mode
212	9.17	-3.37	-	1.11	-1.92	6.18	-3.37	α	-	-
213	8.95	-2.81	-	-0.97	-1.72	6.83	-2.81	α	-	-
214	9.00	-2.97	-	-0.71	-1.42	7.45	-2.97	α	-	-
215	9.02	-3.03	-	-0.56	-1.21	8.05	-3.03	α	-	-
216	9.35	-3.94	-	-0.31	-0.92	8.62	-3.94	α	-	-
217	9.14	-3.37	-	-0.18	-0.72	9.17	-3.37	α	-	-
218	8.87	-2.62	-	0.08	-0.42	9.70	-2.62	α	-	-
219	8.65	-2.05	-	0.22	-0.22	10.20	-2.05	α	-	-
220	8.92	-2.83	-	0.61	0.18	10.68	-2.83	α	-	-
221	9.93	-5.53	-	0.65	0.32	11.13	-5.53	α	-	-
222	10.10	-5.91	-	1.11	0.74	11.56	-5.91	α	-	-
223	9.51	-4.47	-	1.01	0.79	11.96	-4.47	α	-	-
224	9.03	-3.18	-	1.38	1.16	12.34	-3.18	α	-	-
225	8.56	-1.84	-	1.47	1.34	12.69	-1.84	α	-	-
226	8.50	-1.64	-	1.90	1.72	13.02	-1.64	α	-	-
227	8.23	-0.81	-	1.82	1.80	13.32	-0.81	α	-	-
228	7.95	0.10	-	2.26	2.19	13.60	0.10	α	0.32	α
229	7.60	1.31	-	2.19	2.28	13.86	1.31	α	1.96	α
230	7.18	2.66	-	2.90	2.77	14.09	2.66	α	2.02	α
231	1.64	4.27	-	2.68	2.83	14.30	2.68	β^+	2.71	β^+
232	1.01	4.82	-		3.43	14.48	3.43	EC	3.31	EC
233	1.08	6.19	-	3.17	3.36	14.65	3.17	β^+	3.10	β^+
234	0.39	6.68	-		4.32	14.78	4.32	EC	4.50	EC
235	0.12	8.48	-	4.76		14.90	4.76	β^+	3.18	β^+
236	5.87	8.94	-			14.99	8.94	α	7.95	α
237	0.22	9.58	-	-	5.33	15.06	5.33	EC	6.60	EC
238	5.59	10.45	-	-	-	15.11	10.45	α	9.44	α
239	5.25	12.57	-	-	-	15.13	12.57	α	11.88	α
240	5.26	12.49	-	-	-	15.14	12.49	α	11.32	α
241	0.02	13.97	13.90	-	-	15.12	13.90	β^-	8.66	β^-
242	4.98	14.29	-	-	-	15.08	14.29	α	13.07	α
243	0.58	15.91	4.62	-	-	15.02	4.62	β^-	4.25	β^-
244	4.67	16.59	-	-	-	14.94	16.59	α	15.41	α
245	1.21	18.04	3.12	-	-	14.83	3.12	β^-	4.58	β^-
246	0.40	19.13	4.78	-	-	14.71	4.78	β^-	5.97	β^-
247	1.84	24.29	2.21	-	-	14.57	2.21	β^-	5.29	β^-
248	1.63	17.03	2.20	-	-	14.41	2.20	β^-	-	-
249	3.36	17.41	1.15	-	-	14.23	1.15	β^-	-	-
250	1.89	20.21	1.67	-	-	14.03	1.67	β^-	-	-
251	3.28	25.61	0.83	-	-	13.82	0.83	β^-	-	-
252	2.25	27.69	1.11	-	-	13.58	1.11	β^-	-	-
253	3.74	31.68	0.35	-	-	13.33	0.35	β^-	-	-
254	2.70	36.26	0.55	-	-	13.06	0.55	β^-	-	-
255	4.23	39.81	-0.12	-	-	12.77	-0.12	β^-	-	-
256	3.23	42.22	0.01	-	-	12.46	0.01	β^-	-	-
257	4.96	41.11	-0.62	-	-	12.14	-0.62	β^-	-	-
258	4.11	38.11	-0.59	-	-	11.81	-0.59	β^-	-	-
259	5.58	38.97	-1.07	-	-	11.45	-1.07	β^-	-	-
260	4.83	37.94	-1.10	-	-	11.08	-1.10	β^-	-	-

from ^{212}Pu to ^{230}Pu, ^{236}Pu, $^{238-240,242,244}$Pu, α-decay is identified as the most dominant mode, with the theoretical half-lives closely matching experimental trends where data exist. As the isotopic mass increases (i.e ^{231}Pu to ^{235}Pu, a transition is observed toward β^+-decay and EC-decay and subsequently, β^--decay becomes the dominant mode for heavier isotopes with mass number $\geq$ 241. For isotopes where no experimental data exist, the theoretical predictions offer crucial insight into their probable decay modes and stability. In addition, we also evaluated standard deviation as follows;

Table 2. Comparison of half-lives of polonium and astatine isotopes with present work (PW) with experimental values and values predicted by [42].

Parent	Q value	$logT_{1/2}$(s)		
Nuclei	(MeV)	PW	Expt	[42]
^{186}Po	8.50	-4.84	-4.47	-4.83
^{188}Po	8.08	-3.72	-2.85	-3.23
^{190}Po	7.69	-2.50	-3.57	-3.68
^{192}Po	7.32	-1.33	-2.46	-2.39
^{186}Rn	7.86	-2.38	-3.11	-2.31
^{188}Rn	7.61	-1.53	-2.33	-1.56
^{190}Rn	7.34	-0.65	-1.16	-0.68
^{192}Rn	7.04	0.39	0.07	0.38

$$\sigma = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(logT^{th}_{1/2} - logT^{exp}_{1/2})^2} \tag{20}$$

where $\log T^{th}_{1/2}$ and $\log T^{exp}_{1/2}$ represent the logarithmic theoretical and experimental half-lives, respectively, and N denotes number of nuclei taken into account for each decay mode. The calculated standard deviations are 0.975 for α-decay, 1.117 for β^--decay, 3.189 for β^+-decay, and 0.908 for electron capture (EC). The σ values for α, β^-, and EC decays arenear unity, suggesting strong agreement between theoretical and experimental results, whereas the higher value observed for β^+-decay suggests a relatively larger deviation. Although the σ value for β^+-decay is relatively higher, the predicted dominant decay mode among the investigated modes remains in line with findings from experiments, showing that despite the larger deviation in half-life estimation, the theoretical model reliably identifies the correct decay pathway for the studied nuclei. Overall, the table demonstrates that the present work effectively reproduces known decay behaviors while extending predictive power to unexplored plutonium isotopes, offering useful guidance for future experimental investigations into the nuclear structure and decay properties of heavy actinide systems.

The table 2 presents a comparison of the calculated log $T_{1/2}$ values obtained in the present work (PW) with experimental data and the predictions of the systematic model. Overall, the PW results show reasonable agreement with both experimental and literature values, indicating the reliability of the adopted approach. For most isotopes, especially ^{186,188}Po and ^{186,188}Rn, the PW values closely follow the reference model, demonstrating consistency. However, noticeable deviations from experimental data are observed in some cases, such as ^{190,192}Po, where PW slightly overestimates the half-lives. The agreement improves for heavier Rn isotopes, suggesting that the model better reproduces decay properties in this region and captures the underlying nuclear structure effects.

4 Conclusions

In the present study, the competition between different decay modes such as α-decay, $\beta^{\pm}$-decay, electron capture, and spontaneous fission has been systematically investigated for plutonium isotopes in the mass range $212 \leq A \leq 260$. The α-decay half-lives were calculated using the modified generalized liquid drop model, while β-decay and SF half-lives were evaluated using semi-empirical approaches. The calculated decay energies for α-transitions lie between 9.17 MeV and 2.57 MeV, confirming the energetic feasibility of the decay process. The results indicate that α-decay is the dominant mode in $^{212-230}$Pu, ^{236}Pu, $^{238-240}$Pu, ^{242}Pu, and ^{244}Pu due to their relatively shorter half-lives. A transition region is observed in $^{231-235}$Pu, where β^{+}-decay and EC become favorable, while β^{-}-decay dominates for heavier isotopes from ^{241}Pu onwards. The predicted logarithmic half-lives show good agreement with experimental data, with standard deviations of 0.975, 1.117, 3.189, and 0.908 for α, β^{-}, β^{+}, and EC decays, respectively. The model also predicts several new α and β^{-} emitters, highlighting its reliability in unexplored regions.

Overall, the present work provides a comprehensive understanding of decay systematics in plutonium isotopes and offers useful guidance for future experimental studies, synthesis of new isotopes, and applications in nuclear energy and radioactive waste management.

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