Comparison of Various Decay Modes in Translead Region

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Introduction

Nuclei in the region $86 \leq Z \leq 96$, referred to as translead nuclei, represents one of the most intriguing and challenging area in nuclear physics. This region contains the majority of experimentally observed clusters [1], though the predominance of the α-decay mode cannot be overlooked [2]. In addition to these decay modes, spontaneous fission (SF) and weak decay (β^-, β^+, and electron capture (EC)) are also observed with varying probabilities. In this region, the chances of α-decay, cluster decay, and SF are higher Therefore, a comprehensive comparison is essential to understand the detailed properties of nuclei within this region.

In this study, the logarithmic half-lives for various decay modes have been calculated using appropriate formulas for particular decay. For α-decay, cluster decay, SF, and weak decays (β^-, β^+, and electron capture (EC)), we have applied the New Modified Horoi Formula (NMHF) [3], the Improved Tavares and Medeiros (ITM) formula [4], the Modified Bao Formula (MBF) [5], and the formula by Sobhani *et al.* [6], respectively. For comparison purposes, we have focused on the branching ratio (BR).

Formalism

For the α-decay half-lives, NMHF formula [3] is expressed as:

$$log_{10}T_{1/2} = (a\sqrt{\mu}+b)[(Z_\alpha Z_d)^{0.6}Q^{-1/2}-7] + (c\sqrt{\mu}+d)+eI+fI^2+gl(l+1)$$

In this equation, Z_α and Z_d are the proton number of α particle and daughter nucleus, respectively.

For the cluster decay half-lives, ITM formula [4] is given as:

$$log_{10}T_{1/2} = (aZ_c+b)\sqrt{\frac{Z_d}{Q}}+(cZ_c+d) + e\sqrt{I(I+1)}+f\sqrt{l(l+1)}$$

Here, Z_c represents the proton number of emitted cluster.

SF half-lives are calculated by using MBF formula [5], represented as:

$$log_{10}T_{1/2} = a+b\left(\frac{Z^2}{(1-kl^2)A}\right)+ c\left(\frac{Z^2}{(1-kl^2)A}\right)^2+dE_{s+p}$$

The value of k is 2.6 and E_{s+p} is denote the shell plus pairing correction energy.

For all types of weak decay (β^-, β^+, and EC), we have utilized the formula recently proposed by Sobhani *et al.* [6], which is written as:

$$log_{10}T_{1/2} = aZ+bA+cQ^{-1/4}+dI+e, \quad (1)$$

In these equations, Z, N, A, I, and l are the proton number, neutron number, mass number, isospin, and angular momentum of parent nucleus. Q is the disintegration energy for respective decay. The parameters of these formulas are given in their respective references.

Results and discussion

We have systematically analyzed all the cluster decay candidates in the translead region ($86 \leq Z \leq 96$). Since α-decay is the dominant decay mode in this region, and experimentally, clusters have been observed with

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TABLE I: Competition among the various decay modes in the range $86 \leq Z \leq 96$.

Nucleus	$log_{10}T_{1/2}$(sec.)		Branching ratio (in %)					
	Expt.	Th.	α	Cluster	SF	β^-	β^+	EC
^{194}Rn	-3.11	-3.66	41.17	58.70	0.00	-	0.03	0.10
^{200}Fr	-2.15	-2.99	93.51	6.08	0.00	-	0.11	0.30
^{225}Ra	6.11	7.95	0.11	9.41×10^{-11}	0.00	99.89	-	-
^{224}Ac	4.00	3.81	66.33	1.17×10^{-14}	0.00	1.46	21.88	10.34
^{225}Th	6.11	7.95	0.11	9.41×10^{-11}	0.00	99.89	-	-
^{227}Pa	3.36	4.03	1.05	1.68×10^{-17}	0.00	-	35.40	63.55
^{204}U	-	-6.06	71.93	1.87×10^{-09}	28.03	-	0.00	0.03
^{229}Np	2.38	2.52	19.24	5.08×10^{-17}	0.00	-	50.20	30.56
^{233}Pu	3.10	2.94	14.42	4.01×10^{-17}	0.00	-	50.36	35.22
^{215}Am	-	-4.41	88.05	4.33×10^{-14}	11.57	-	0.05	0.33
^{217}Cm	-	-6.71	29.29	1.30×10^{-13}	70.70	-	0.00	0.00

BRs of approximately 10^{-18} or higher, one isotope from each Z number that exhibits strong competition with α-decay, with BRs exceeding 10^{-18}, has been selected for detailed analysis. This approach allows for a clear comparison among the aforementioned decay modes. We have calculated half-lives and evaluated the competition of all probable decay modes on equal footing, using carefully selected empirical formulas.

First, we have calculated the theoretical total half-lives using the following formula:

$$\frac{1}{T_{1/2}^{\text{Th.}}} = \frac{1}{T_{1/2}^{\alpha}} + \frac{1}{T_{1/2}^{cluster}} + \frac{1}{T_{1/2}^{\beta^-}} + \frac{1}{T_{1/2}^{\beta^+}} + \frac{1}{T_{1/2}^{EC}} + \frac{1}{T_{1/2}^{\text{SF}}}$$

In these theoretical half-lives, the l values are calculated using the selection rule [8]. The spin-parity and Q values are sourced from NUBASE2020 [7]. After calculating $T_{1/2}^{\text{Th.}}$, we have determined the BR using the following expression:

$$BR = \frac{T_{1/2}^{Th.}}{T_{1/2}^{\alpha/Cluster/SF/\beta^-/\beta^+/EC}} \qquad (2)$$

This comparison of BR is clearly visible in Table I. The table clearly shows that the probability of α-decay is usually higher; however, in the case of ^{225}Ra, β^--decay predominantly occurs with a probability of 99.89 %. Additionally, ^{224}Ac exhibits some probability of β^- emission. The emission probability of cluster from ^{194}Rn is higher than that of α-decay. The experimental BR limit for cluster emission is approximately 10^{-18}, and all the nuclei selected for comparison fall within this range, indicating a greater likelihood of cluster emission in this region. In the translead region ($86 \leq Z \leq 96$), β^+/EC decay modes are significant alongside α-decay.

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