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Probable shell and sub-shell closure in ^{253}Rf decay chain

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Introduction

The stability of various heavy and superheavy nuclei takes their primary description from the shell structure of their respective nucleus. This usually requires a good understanding of the quantum nature of the underlying nuclear structure. The α-decay, which is an important tool to investigate the underlying structure and stability, earlier has been theoretically described by quantum tunnelling effect [1].

In the present work, we have adopted the preformed cluster-decay model (PCM) which is based on quantum mechanical fragmentation theory (QMFT) [2] for the estimation of the α-decay half-lives. The PCM holds the assumption that an α-particle is conceived within the parent nucleus before its penetration across the potential barrier built from the interplay of the Coulomb and nuclear potential. In this study, The relativistic mean-field (RMF) based R3Y nucleon-nucleon potential is folded with the RMF densities to obtain the nuclear potential (see Ref. [3] for elaborate details). The WKB approximation is employed for the estimation of the penetration probability P.

In this study, the neck-length parameter, ΔR, between the decaying fragments is varied within the nuclear proximity range i.e. $0 \leq \Delta R \leq 2$ fm [3]. To ensure the accuracy of present calculation, the α-decay energies (Q_α-values) are taken from the experimental measurements [4]. The overall effort is geared at investigating decay properties of the newly discovered neutron-deficient ^{249}No isotope from the ^{253}Rf decay chain [5].

Theoretical formalism

In the RMF framework, the interactions between the many-body system of nucleons and mesons are expressed via the non-linear RMF Lagrangian density [3]. The R3Y (NL3*) NN interaction plus the single nucleon exchange effect is given as [3],

$$V_{eff}^{R3Y}(r) = \frac{g_\omega^2}{4\pi}\frac{e^{-m_\omega r}}{r} + \frac{g_\rho^2}{4\pi}\frac{e^{-m_\rho r}}{r} - \frac{g_\sigma^2}{4\pi}\frac{e^{-m_\sigma r}}{r} + \frac{g_2^2}{4\pi} r e^{-2m_\sigma r} + \frac{g_3^2}{4\pi}\frac{e^{-3m_\sigma r}}{r} + J_{00}(E)\delta(s), \quad (1)$$

with the ranges in fm and strength in MeV. The decay constant and half-life is calculated within the PCM [2, 3] as

$$\lambda = \nu_0 P_0 P, \qquad T_{1/2} = \frac{\ln 2}{\lambda}. \quad (2)$$

The preformation probability P_0 is calculated from the Deng & Zhang formula [6].

Result and Discussions

In the PCM framework, a constant scaling factor of 10^{-4} is generally required for the calculation of half-lives [7]. However, it has been recently demonstrated that this conjecture is susceptible to change at the shell closure and thus, randomness sets it [8]. Fig. 1 reveals the variation of the PCM scaling factor for the α-emitting ^{253}Rf decay chain. From the figure, it is obvious that the smooth systematic trend is altered at ^{245}Fm and ^{233}Pu (indicated with

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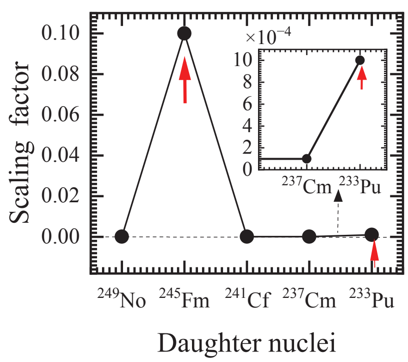

FIG. 1: Variation in the scaling factors of ^{253}Rf decay chain with the preformed cluster model (PCM). The red arrows indicates suspected shell/sub-shell closures. The inset shows a magnified view of randomness/unusual increase in the scaling factor for ^{233}Pu daughter nuclei.

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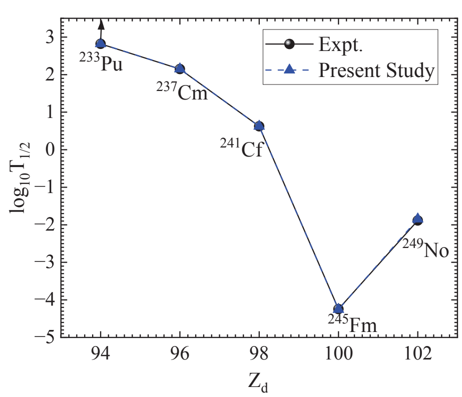

FIG. 2: Logarithmic half-lives of systems within the ^{253}Rf decay chain versus the proton number of their respective daughter nucleus. The daughter nuclei are mentioned beneath their corresponding data point. The black arrow indicates that only the experimental lower limit is available for ^{237}Cm $\rightarrow^{233}$Pu $+\alpha$. The experimental half-lives are taken from [4].

a red upward arrow) suggesting the possibility/presence of shell and sub-shell closures respectively. In other words, the ^{245}Fm is found to be shell stabilized. Interestingly, this result is consistent with the recent findings of Das *et al.* [9]. The inset shows a magnified view of the abrupt increase in the scaling factor at ^{233}Pu. The effect and implication of these randomnesses are evident in the α-decay half-lives.

Figure 2 shows the profile of the logarithmic half-lives as a function of the proton number of the daughter nuclei. The lowest minima are found at $N = 100$ corresponding to ^{245}Fm daughter nuclei (from ^{249}No $\rightarrow^{245}$Fm $+\alpha$) which is characteristic of its shell stability whereas the highest half-life values are found at ^{233}Pu indicating a shell/sub-shell closure. This gives credence to the aforementioned randomness in their respective scaling factors. Other than the point of shell stability, the $\log_{10} T_{1/2}$ values are found to decrease with decreasing N/Z ratio or vice versa. Generally, the half-lives calculated using RMF are consistent with the experimental data and also satisfy the measured lower limit for ^{233}Pu.

Acknowledgments

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