Theoretical estimate of a realistic preformation probability in the cluster decay process

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Introduction

Usually, the emission of clusters from heavy nuclei is treated as a highly asymmetric fission process [1]. Its prediction dates back to 1980 and experimentally confirmed by Rose and Jones [2]. Theoretically, its description can be grouped into two classes. The first assumes that clusters are formed as the decaying parent undergoes repeated deformation until it reaches the saddle point. On the other hand, the second (e.g. the preformed cluster decay model (PCM) [3]) assumes that clusters are conceived inside the parent nuclei and thus requires the estimation of a precise preformation probability (P_0). In this regard, several (P_0) formulae have been put forward with reasonable fitting to the experimental data. However, from literature survey, the mechanism of cluster pre-formation is poorly understood.

In this study, a concerted effort is given to the investigation of the preformation probability from the basic theoretical underpinnings and influential parameters in the cluster-decay process. We have employed the PCM framework which stems from the quantum mechanical fragmentation theory (QMFT) [3] for the calculation of the cluster decay half-lives. The relativistic mean-field (RMF) based R3Y nucleon-nucleon potential and the RMF densities are folded to deduce the nuclear potential (exhaustive details are given in Ref. [1]). The WKB approximation is employed for the estimation of the penetration probability P.

Following the analysis in Ref. [1], the neck-length parameter, ΔR, between the decaying fragments is fixed at 1.0 fm. The decay energies (Q-values) are taken from Ref. [4] and the calculated half-lives are compared with experimental measurements [5]. In this short essay, the ground state emissions of ^{28,30}Mg and ^{32,34}Si from ^{236,238,240}Pu isotopes are examined (i.e. $^{236,238}\text{Pu} \rightarrow^{A-208} Mg +^{208} Pb$ and $^{238,240}\text{Pu} \rightarrow^{A-206} Si +^{206} Pb$).

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 [1]. Like the phenomenological M3Y [6], the relativistic R3Y (NL3*) NN interaction plus the single nucleon exchange effect is given as [1],

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

with the ranges in fm and strength in MeV. The decay constant and half-life is calculated within the PCM [1, 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 Ref. [7].

Result and Discussions

It is customarily known that the preformation probability P_0 of a decaying system entails its structural and decay properties. Here, the P_0 is predicated on the experimental evidence on the possibility of different cluster

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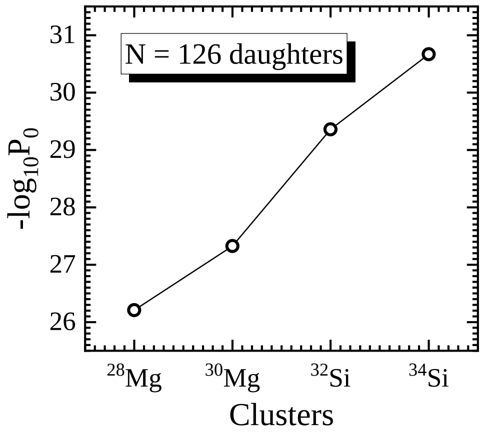

FIG. 1: The calculated preformation probability P_0 for actinides yielding $N = 126$-daughters using the newly proposed formulae in Ref. [7]

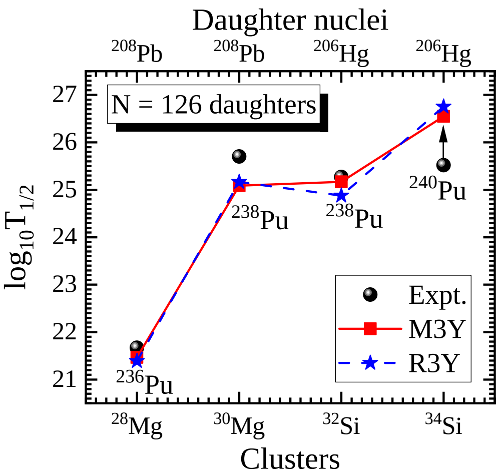

FIG. 2: The estimated logarithmic half-lives for the different emitted clusters from ^{236,238,240}Pu isotopes at a fixed neck-length ΔR=1.0 fm for M3Y and R3Y NN potentials. The experimental are taken from Ref. [5].

emission from the same parent [5] and similar established influential parameters. Fig. 1 shows the variation of the P_0 with the considered clusters from ^{236,238}Pu $\rightarrow^{A-208} Mg +^{208} Pb$ and ^{238,240}Pu $\rightarrow^{A-206} Si +^{206} Pb$ reaction systems. It is worth mentioning that, for the sake of presentation, the negative logarithmic scale is used here to magnify the actual values. From the figure, it is obvious that one of the prevailing influence on P_0 is the mass of the emitted cluster. Specifically, P_0 is found to increase with increasing cluster mass. Although the relative cluster masses under study differs by an additive factor of 2, no proportionality is observed. This infers that cluster preformation is usually influence by other parameters other than the cluster mass A_c. Thus, we conclude that the popular cluster-mass dependent Blendowske and Walliser formula [8] is not sufficient for the description of the underlying mechanism of cluster emission.

Fig. 2 depicts the profile of the logarithmic half-lives versus the different cluster masses at a fixed neck-length ΔR=1.0 fm for M3Y and R3Y NN potentials. The parent nuclei are included under each data point in the figure. The predictive power of the relativistic R3Y NN potential (blue stars with dash lines) as compared to the phenomenological M3Y NN potential (red squares with solid lines) is clearly demonstrated in the figure. With the inclusion of the new P_0 formula, the estimated $\log_{10} T_{1/2}$ in each case are found to be consistent with the experimental data (black spheres) [5]. Interestingly, the half-lives values of both M3Y and R3Y for ^{240}Pu $\rightarrow^{34} Si +^{206} Pb$ are consistent with the experimental lower limit.

Acknowledgments

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