Dynamics of p-induced fission of actinide nuclei using collective clusterization approach

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Introduction

The nuclear fission phenomenon discovered in the late 1930s, plays a crucial role in fundamental and applied nuclear research. Apparently, the fission process is of great significance as it aids in production of various new isotopes, their explicit study and applications. The fission decay mode may either be obtained through reactions induced by light particles or heavy ions (Z≥2,A≥4). Over the years, with advancement in technology, the interest in nucleon induced fission of actinide nuclei has been of considerable interest, as it provides an opportunity to explore the properties of actinide nuclei involved in these reactions and probability of various decay modes accompanying the dominant fission decay. In view of this, an attempt has been made to study the dynamics of p-induced fission over a wide range of incident energies in reference to experimental findings of [1]. The main aim of present work is to investigate the fission properties of p+^{232}Th→ ^{233}Pa*, p+^{238}U→ ^{239}Np* and p+^{239}Pu→ ^{240}Am* reactions at common incident energies E_p=26.5 MeV and 62.9 MeV using dynamical cluster decay model (DCM) [2]. The focus of this study is to (i) analyze the fragment mass distributions, (ii) examine the role of target mass and incident energy on decay path, (iii) measure the fission decay cross-sections of actinide nuclei, (iv) examine the relative role of barrier modification in context of chosen reactions.

Dynamical Cluster-decay Model

The dynamical cluster-decay model (DCM) has been widely used to study decay properties of hot and rotating nuclei. It is based on quantum mechanical fragmentation theory, and is worked out in terms of collective coordinates of mass and charge asymmetries $\eta_A = \frac{A_1-A_2}{A_1+A_2}$ and $\eta_Z = \frac{Z_1-Z_2}{Z_1+Z_2}$ (where 1 and 2 stand for heavy and light fragments) and relative seperation cooridinate, R. Using the decoupled approximation, the decay cross-section, in terms of partial waves can be read as

$$\sigma = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{max}}(2\ell+1)P_0P;\ k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}}, \quad (1)$$

where, P_0 the preformation probability, refers to η-motion and P the penetrability, refers to R-motion. The preformation probability (P_0) in Eq.(1) is obtained by solving the stationary Schrödinger equation and is given as:

$$P_0 = |\psi(\eta(A_i))|^2\sqrt{B_{\eta\eta}}\frac{2}{A_{CN}}. \quad (2)$$

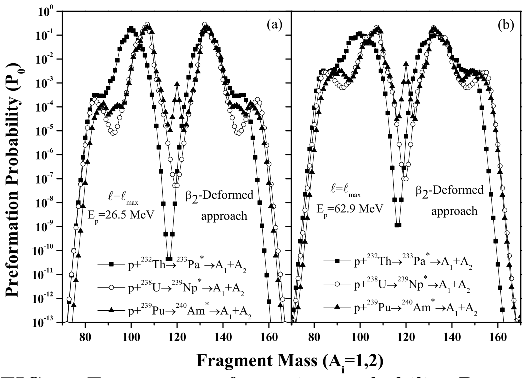

FIG. 1: Fragment preformation probability P_0 as a function of heavy mass fragments for ^{233}Pa*, ^{239}Np* and ^{240}Am* nuclei plotted at (a) E_n=26.5 MeV and (b) 62.9 MeV for the use of quadruple (β_2) deformed approach and at maximum ℓ-value.

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TABLE I: The DCM calculated fission cross sections for ^{233}Pa*, ^{239}Np*, ^{240}Am* nuclei at E_n=26.5 MeV and 62.9 MeV, compared with the experimental data [1].

Compound nucleus	ℓ_{max} ($\hbar$)	$\triangle R$ (fm)	A$_2$	$\sigma^{DCM}_{Fission}$ (mb)	$\sigma^{Expt.}_{Fission}$ (mb)
$E_p = 26.5 MeV$					
^{233}Pa*	133	1.273	95-106	1194	1190±60
^{239}Np*	139	1.244	101-112	1546	1540±77
^{240}Am*	133	1.237	101-110	1756	1760±88
$E_p = 62.9 MeV$					
^{233}Pa*	142	1.390	95-106	1068	1550±78
^{239}Np*	149	1.365	100-110	1234	1980±99
^{240}Am*	141	1.360	101-110	1236	2320±116

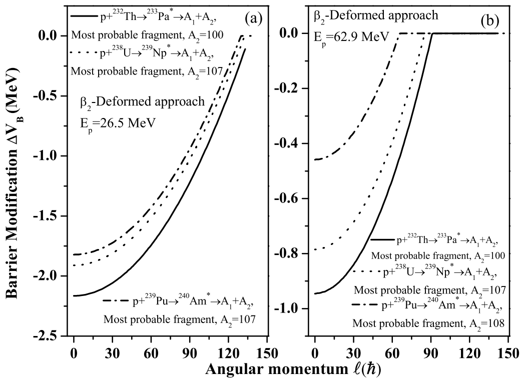

FIG. 2: Variation of ΔV_B as a function of angular momentum for ^{233}Pa*, ^{239}Np* and ^{240}Am* nuclei at (a) E$_p$=26.5 MeV and (b) E$_p$=62.9 MeV.

It is worth noting that, the multipole deformations $\beta_{\lambda i}$ (λ=2, 3, 4), and orientations θ_i (i=1,2) of two nuclei or fragments have been duly incorporated in DCM along with temperature (T) effects.

Results and Discussions

To analyze the fragment mass distribution of ^{233}Pa*, ^{239}Np* and ^{240}Am* nuclei the fragment preformation probability (P$_0$) is plotted as a function of fragment mass (A$_2$) at E$_p$=26.5 MeV and 62.9 MeV as shown in Fig.1(a) and (b) respectively. P$_0$ is the probability with which the fragment is preformed before it comes out of the compound system environment. It is evident from the figure that fragment mass distribution is asymmetric for ^{233}Pa*, ^{239}Np* actinide nuclei at both incident energies. However, the mass distribution of heavier nucleus, i.e. ^{240}Am*, is relatively symmetric at both the energies. It is worth noting that the fission cross-section calculated for the optimum choice of neck-length parameter ΔR, are found to have nice agreement with experimental data at below barrier energy, i.e. E$_p$=26.5 MeV while at higher energy the same are significantly underestimated as evident from Table-I. From the lower DCM cross-sections at higher E$_p$=62.9 MeV, it may be concluded that, in agreement with experiment observation the proton induced reaction for actinide nuclei exhibit some other competing phenomenon in addition to the observed fission decay channel. The maximum angular momentum (ℓ_{max}), neck-length parameter (ΔR) and the contributing fission fragments (A$_2$) are tabulated in Table-I along with DCM cross-section, compared with experimental data. The choice of ΔR for the best fit to the data allows us to define the effective "barrier lowering" parameter ΔV_B which is difference between the actual used barrier, $V(R_a, \ell)$, and the calculated barrier $V_B(\ell)$, i.e. $\Delta V_B(\ell) = V(R_a, \ell) - V_B(\ell)$. The variation of barrier modification as a function of angular momentum for most probable fission fragments for all three actinide nuclei at extreme energies is shown in Fig.2(a) and (b). It is observed that at both energies, relatively larger barrier modification (in magnitude) is needed at lower angular momentum. Moreover, at lower energy, the barrier modification needed to attain the experiment fission cross-section is considerably large as compared to higher energy. The above mentioned fragmentation and barrier modification analysis is expected to impart further insight in context of p-induced dynamics.

References

[1] S. Isaev *et al.*, Nucl. Phys. A **809**, 1 (2008).

[2] A. Kaur *et al.*, Nucl. Phys. A **941**, 152 (2015).