Signatures of non-coplanarity in hot fusion reaction ^{12}C+^{93}Nb via P_{CN} and P_{surv} determined on dynamical cluster-decay model

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Introduction

In recent works [1, 2], we introduced and estimated for the first time the compound nucleus (CN) formation probability P_{CN} and the survival probability P_{surv}, using the dynamical cluster-decay model (DCM) of Gupta and collaborators [3], and applied to various "hot" fusion reactions. Interestingly, independent of the nuclear interaction potentials used, the variation of P_{CN} and P_{surv} on CN excitation energy E*, fissility parameter χ, CN mass A_{CN} and Coulomb parameter Z_1Z_2, allow us to classify the considered compound systems into three groups, namely, weekly fissioning, radioactive and strongly fissioning superheavy nuclei. For ^{12}C+^{93}Nb reaction, forming ^{105}Ag*, only co-planar ($\Phi = 0^0$) nuclei were considered, which gave arise to an unrealistic result of P_{CN} belonging to the superheavy group (^{292}Fl*, ^{286}Cn*) [1], and P_{surv} to weakly fissioning group of nuclei (^{164}Yb*, $^{176-196}$Pt*, ^{202}Pb* and ^{213,217}Fr*) [2].

In this work, we allow the non-coplanar degree-of-freedom ($\Phi \neq 0^0$) and apply the DCM to ^{12}C+^{93}Nb→^{105}Ag* reaction. The important result is that, with $\Phi \neq 0^0$, both P_{CN} and P_{surv} belong to the weekly fissioning nuclei, the group to which ^{105}Ag* belongs.

Methodology

Defining the (total) fusion cross section (also, called the capture cross section)

$$\sigma_{fus} = \sigma_{CN}+\sigma_{nCN} = \sigma_{ER}+\sigma_{ff}+\sigma_{nCN} \quad (1)$$

where, the CN cross section σ_{CN} is the sum of evaporation residue (ER) cross section σ_{ER} and the fusion-fission cross section σ_{ff}. σ_{nCN} is the non-CN contribution. Then,

$$P_{CN} = \frac{\sigma_{CN}}{\sigma_{fus}} = 1 - \frac{\sigma_{nCN}}{\sigma_{fus}}, \quad (2)$$

and P_{surv}, the emission of light particles (LPs) or neutrons *w.r.t.* the fusion-fission process, given as

$$P_{surv} = \frac{\sigma_{ER}}{\sigma_{CN}}. \quad (3)$$

In order to calculate the above quantities within the DCM, we introduce the collective coordinates of mass (and charge) asymmetries $\eta = (A_1 - A_2)/(A_1 + A_2)$ (and $\eta_Z = (Z_1 - Z_2)/(Z_1 + Z_2)$) and relative separation R, with the multipole deformations $\beta_{\lambda i}$ (λ=2, 3, 4; i=1, 2, referring to heavy and light decay fragments), orientations θ_i and azimuthal angle Φ. Then, in terms of these coordinates, including the temperature T and angular momentum ℓ effects, the compound nucleus decay/fragments-formation cross section for ℓ partial waves is defind for each pair of exit/ decay channel as

$$\sigma_{A_1,A_2} = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{max}}(2\ell+1)P_0P; \quad k = \sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}} \quad (4)$$

where P_0 is fragment preformation probability, referring to η motion at fixed R-value and P, the barrier penetrability, to R motion for each η-value, both dependent on T and ℓ. μ is the reduced mass with m as the nucleon mass. ℓ_{max} is the maximum angular momentum, defined for light-particle evaporation residue cross section σ_{ER} →0. Then, it follows from Eq. (4) that

$$\sigma_{ER} = \sum_{A_2=1}^{4 \text{ or } 5}\sigma_{(A_1,A_2)} \quad \text{or} \quad = \sum_{x=1}^{4 \text{ or } 5}\sigma_{xn}, \quad (5)$$

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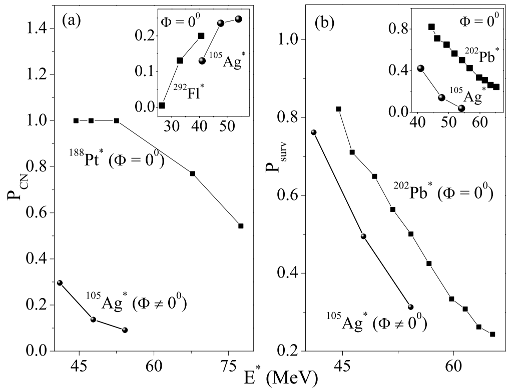

FIG. 1: Comparison of $\Phi = 0^0$ and $\Phi \neq 0^0$ cases of P_{CN} and P_{surv} in the ^{12}C+^{93}Nb reaction.

$$\sigma_{ff} = 2 \sum_{A_2=5 \text{ or } 6}^{A/2} \sigma_{(A_1,A_2)}. \qquad (6)$$

The same formula (4) is also applied to the nCN decay process, calculated here as the quasi-fission (qf) decay channel where P_0=1 since for qf the incoming target and projectile nuclei can be considered to have not yet lost their identity, and then P is calculated for the *incoming channel*.

For non-coplanar nuclei ($\Phi \neq 0^0$), we use the same formalism as for $\Phi = 0^0$ (Eq. (4)), but by replacing for the out-of-plane nucleus (i=1 or 2) the corresponding radius parameter $R_i(\alpha_i)$ with its projected radius parameter $R_i^P(\alpha_i)$ (=$R_i(\alpha_i)\ \cos\Phi$), in both the Coulomb and proximity potentials. For Coulomb potential, it enters via $R_i(\alpha_i)$ itself, and for the proximity potential via the definitions of both the mean curvature radius $\bar{R}$ and the shortest distance s_0 [4]. Thus, Φ-dependence of projected radius vector $R_i^P(\alpha_i)$ is also contained in the maximized $R_j^P(\delta_j^{max})$. For further details, see Ref. [4]. Then, for the nuclear proximity potential, denoting V_P^{12} as the potential for nucleus 1 to be out-of-plane, and V_P^{21} for the nucleus 2 to be out-of-plane, the effective $V_P = [(V_P^{12} + V_P^{21}]/2$.

Calculations and Results

As already noted above, for ^{105}Ag* with non-coplanar degree-of-freedom ($\Phi \neq 0^0$), the striking result is its shifting of P_{CN} from superheavy to weakly fissioning group of nuclei. Fig. 1(a) shows the comparison of P_{CN} as a function of, say, E^* for $\Phi = 0^0$ and $\Phi \neq 0^0$ cases of ^{105}Ag*, where, respectively, one ($\Phi = 0^0$, inset) is an increasing function, and the other ($\Phi \neq 0^0$) showing an opposite variation of decreasing function of E^*, similar to, say, superheavy ^{292}Fl*, and weekly fissioning ^{188}Pt*. This happens because for ^{105}Ag*, in going from $\Phi = 0^0$ to $\Phi \neq 0^0$, the CN cross section σ_{CN} decreases (consequently, $\sigma_{nCN}^{Cal.}$ increases), instead of increases, with increasing E^*. On the other hand, for P_{surv} of ^{105}Ag* in Fig. 1(b), the variations in both cases ($\Phi = 0^0$ and $\Phi \neq 0^0$) are similar, i.e., decreasing with increasing E^*, like in weakly fissioning nuclei, illustrated for ^{202}Pb*. Putting the results of both P_{CN} and P_{surv} together, for $\Phi \neq 0^0$, ^{105}Ag* belongs to the category of weakly fissioning nuclei, both decreasing with increasing E^*. Note that the results of weakly fissioning nuclei, used for comparisons, are for $\Phi = 0^0$, and need be extended to the case of $\Phi \neq 0^0$.

Acknowledgments

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References

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