Non-coplanarity in fusion reaction ^{64}Ni+^{100}Mo→^{164}Yb* studied on the dynamical cluster-decay model

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Introduction

The predominantly measured fusion cross-sections for ^{64}Ni+^{100}Mo reactions are the fusion-evaporation residue cross-sections σ_{ER} [1], known for the fusion-hindrance phenomenon in ccc [1], requiring "barrier modification" effects at sub-barrier energies in both the ccc [2] and the extended-Wong model for use of the nuclear proximity potential both as the pocket formula [3] and one derived from semiclassical extended Thomas Fermi approach based on Skyrme energy density formalism [4]. The dynamical cluster-decay model (DCM) also supports the property of "barrier lowering" for such Ni-based reactions at sub-barrier energies, studied for non-coplanar ($\Phi \neq 0^0$) nuclei only for the case of ^{64}Ni+^{64}Ni reaction [5]. For ^{64}Ni+^{100}Mo reaction, only the case of co-planar nuclei (Φ=0^0) is studied for the DCM [6]. For nuclear proximity potential, the pocket formula is used in both the studies [5, 6].

In this contribution, we include in the above stated study of ^{64}Ni+^{100}Mo reaction [6], based on DCM, the non-coplanar ($\Phi \neq 0^0$) degree of freedom with a view to see if "barrier modification" phenomenon for σ_{ER} still exists in this reaction. We again use the pocket formula for nuclear proximity potential, and include multipole deformations up to hexadecapole (β_2 - β_4) which means using hot "compact" orientations (θ_{ci}, Φ_c; i=1,2). However, the "barrier modification" effects still remain the same as for Φ=0^0 case, though with reduced amplitude, meaning thereby that it is a characteristic property of reactions with predominant evaporation residue cross-sections σ_{ER}.

Dynamical cluster-decay model

The dynamical cluster-decay model (DCM) is based on collective coordinates of mass (and charge) asymmetry η (and η_z) [η=(A_1-A_2)/(A_1+A_2); η_z=(Z_1-Z_2)/(Z_1+Z_2)], and relative separation R. For the de-coupled η, R-motions, in terms of the ℓ-partial waves, the DCM defines the fragment formation or compound nucleus (CN)-decay cross section [6]

$$\sigma = \frac{\pi}{k^2}\sum_{\ell=0}^{\ell_{max}}(2\ell+1)P_0P_\ell; \qquad k=\sqrt{\frac{2\mu E_{c.m.}}{\hbar^2}}. \tag{1}$$

Here, the penetrability P_ℓ, refers to the R-motion, given by the WKB integral

$$P_\ell = \exp\left[-\frac{2}{\hbar}\int_{R_a}^{R_b}\{2\mu[V(R,T)-V(R_a,T)]\}dR\right], \tag{2}$$

with V(R_a)= V(R_b)= TKE(T)=Q_{eff} for the two turning points. Q_{eff} is effective Q-value of decay process (=TKE), and R_a=R_1(η,T)+R_2(η,T)+ΔR(η,T) with

$$R_i(\alpha_i) = R_{0i}(T)[1+\sum_\lambda \beta_{\lambda i}Y_\lambda^{(0)}(\alpha_i)]. \tag{3}$$

The P_0 is given by the solution of stationary Schrödinger equation in η, at a fixed R,

$$\left\{-\frac{\hbar^2}{2\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta}\frac{1}{\sqrt{B_{\eta\eta}}}\frac{\partial}{\partial\eta} + V(R,\eta,T)\right\}\psi^\nu(\eta) = E^\nu\psi^\nu(\eta), \tag{4}$$

with ν=0,1,2,3.... for ground- (ν =0) and excited-state solutions. Then, the preformation factor

$$P_0(A_i) = |\psi_R(\eta(A_i))|^2\frac{2}{A}\sqrt{B_{\eta\eta}}. \tag{5}$$

The effects of "barrier lowering" for each decay channel, defined for each ℓ as the difference between V_B^ℓ and $V^\ell(R_a)$, the actually calculated and the actually used barriers, is

$$\Delta V_B^\ell = V^\ell(R_a) - V_B^\ell. \tag{6}$$

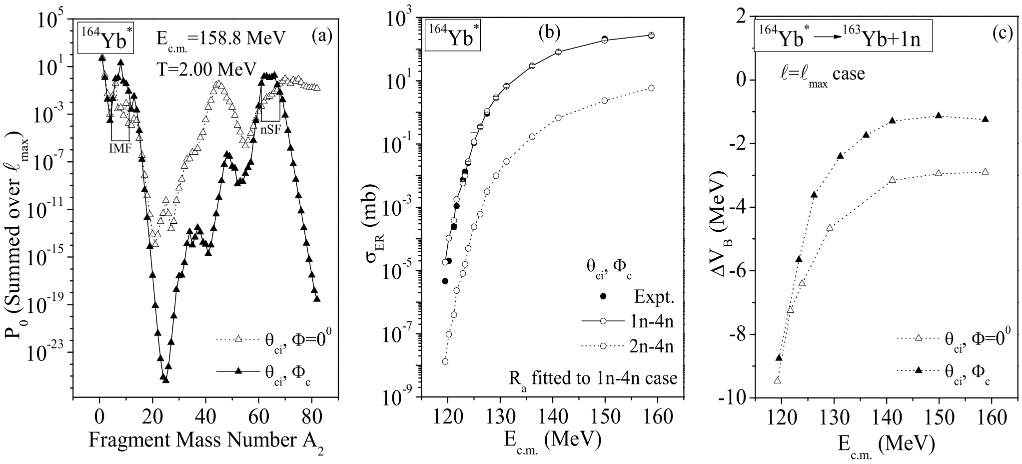

FIG. 1: (a) DCM calculated ℓ-summed $P_0(A_2)$ for CN $^{164}Yb^*$ formed in ^{64}Ni+^{100}Mo reaction at $E_{c.m.}$=158.8 Mev, taking two different ΔR's (one each for ER and ff) for a best fit to σ_{ER} data, for both cases of Φ=0^0 and $\Phi \neq 0^0$; (b) The best fitted σ_{ER}(1n-4n)($E_{c.m.}$) for the dacay of $^{164}Yb^*$, compared with the experimental data [1]. Also shown is the (2n-4n) contribution; (c) Barier lowering parameter $\Delta V_B(E_{c.m.})$ at ℓ=ℓ_{max} for best fitted σ_{ER}(1n) for Φ=0^0 and $\Phi \neq 0^0$ cases.

Calculations and results

First of all, we look for the possible decay processes in ^{64}Ni+^{100}Mo reaction, illustrated in Fig. 1(a) for the calculated ℓ-summed P_0, both for the cases of Φ=0^0 and $\Phi \neq 0^0$. We notice that, in addition to ER being the most favored process in both cases, an almost complete fusion-fission (ff) (=IMFs+HMFs+nSF+SF, sum of intermediate and heavy mass fragments, IMFs and HMFs, the near-symmetric and symmetric fission, nSF and SF) is predicted for Φ=0^0 case, which reduces to only the IMFs (A_2=5-11) and nSFs (A_2=61-68) for $\Phi \neq 0^0$. Interestingly, the nSF occurs only at the, not yet measured, highest couple of $E_{c.m.}$'s, compatible with the CASCADE predictions [1]. Experimental verification is called for the role of Φ.

Fig. 1(b) shows the DCM calculated $\sigma_{ER}(E_{c.m.})$, compared with experimental data for the CN ^{164}Yb* formed in ^{64}Ni+^{100}Mo [1], for the best fitted neck-length parameter ΔR (equivalently, "barrier lowering" parameter $\Delta V_B(E_{c.m.})$). We have also plotted here the case of ER consisting of 2n-4n, stressing the importance of 1n-decay of ^{164}Yb*. Finally, Fig. 1(c) shows the variation of $\Delta V_B(E_{c.m.})$ at ℓ=ℓ_{max} for $\Phi \neq 0^0$, compared with Φ=0^0 case. Note that in going from Φ=0^0 to $\Phi \neq 0^0$, the magnitude of $\Delta V_B(E_{c.m.})$ reduces considerably, particularly at higher energies.

Concluding, "barrier lowering" is essential in reactions with dominant evaporation residue cross-sections, even when non-coplanar degree of freedom Φ is included in the DCM.

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