Effect of inclusion of Multipole deformations and Non-coplanarity on non-compound nucleus contribution in Heavy-ion reactions

Hemdeep,* Sahila Chopra, Pooja Kaushal, and Raj K. Gupta
Department of Physics, Panjab University, Chandigarh - 160014, INDIA

Introduction

Recently, we studied the formation and decay of ^{220}Th* compound nucleus within the Dynamical Cluster-decay Model (DCM)[1], formed through four different entrance channels ^{16}O+^{204}Pb, ^{40}Ar+^{180}Hf, ^{48}Ca+^{172}Yb and ^{82}Se+^{138}Ba at near barrier energies [2]. The calculations were made for quadrupole deformations (β_{2i}) with optimum orientations θ_i^{opt} of the two nuclei lying in the same plane (co-planar nuclei, Φ=0^o). It was found that the total ER cross section σ_{ER} ($=\sum_{x=1}^{5}\sigma_{xn}$) and their 3n and 5n decay channels are fitted exactly, but the 4n channel required an amount of non-compound nucleus (nCN) contribution treated as quasi-fission like process. Here in this work, the role of higher multipole deformations, i.e., the effects of octupole and hexadecapole deformations (β_{3i}, β_{4i}) and compact orientations θ_{ci} for non-coplanar degree of freedom ($\Phi \neq 0^o$) on the nCN cross section is studied.

The values of β_{3i}=0 for most of the of nuclei and the effect of β_{4i} deformations is small, rather negligible, on θ_i^{opt} orientations when β_{4i} are negative or small positive but the θ_i^{opt} could change by as much as 20^o when β_{4i} have larger positive values (orientation θ_i^{opt} is then denoted as "compact orientation" θ_{ci}), depending on the magnitude of β_{2i} [3]. Further, we find from our earlier studies that the inclusion of Φ, i.e, for non-coplanar collisions, the nCN contribution reduces to zero and hence the decay becomes a pure compound nucleus decay. Thus, it seems essential to use β_{2i}-β_{4i} deformations with compact orientations θ_{ci}, for coplanar or non-coplanar collisions.

*Electronic address: hemdeep08@gmail.com

Methodology

The quantum mechanical fragmentation Theory (QMFT)-based Dynamical cluster-decay mode l(DCM) [4] is worked out in terms of the 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 coordinate R, with β_{2i}-β_{4i} deformations; i=1,2 and "compact" orientations θ_{ci} for coplanar (azimuthal angle Φ=0^o) and for non-coplanar nuclei $\Phi \neq 0^o$. In terms of these coordinates, for ℓ partial waves, the CN decay cross section for each fragmentation (A_1, A_2) is defined as

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

where P_0 is preformation probability referring to η motion and P, the penetrability, to R motion, both dependent on angular momentum ℓ and temperature T. The same formula is applicable to the nCN decay process, calculated as the quasi-fission (qf) decay channel, where P_0=1 for the *incoming channel* since the target and projectile nuclei can be considered to have not yet lost their identity. The collective fragmentation potential $V_R(\eta, T)$, that brings in the structure effects of the CN in the formalism, used for calculating P$_0$, is given, according to the Strutinsky renormalization procedure ($B = V_{LDM} + \delta U$; B is binding energy), as

$$\begin{aligned} V_R(\eta,T) &= -\sum_{i=1}^{2} B(A_i,\beta_{\lambda_i},T) \\ &+ V_P(R,A_i,\beta_{\lambda_i},\theta_i,\Phi,T) + V_C(R,Z_i,\beta_{\lambda_i},\theta_i,\Phi,T) \\ &+ V_\ell(R,A_i,\beta_{\lambda_i},\theta_i,\Phi,T) \quad (2) \end{aligned}$$

P reprents the R-motion and is given by WKB integral.

TABLE I: DCM calculated 3n, 4n and 5n decay channel cross sections of ^{220}Th* at E*=39.9 MeV, with $\sigma^{Cal.1}$ as the one wih inclusion of higher multipole deformations for $\Phi = 0^o$, and $\sigma^{Cal.2}$ same as Cal.1 for $\Phi \neq 0^o$, compared with the case of (β_{2i}, θ_i^{opt})-calculation of Ref. [1] and experimental data [2].

			DCM-Cal.1		DCM-Cal.2		
		(β_{2i} with θ_i^{opt})	(β_{2i}-β_{4i} with θ_{ci})				
			($\Phi = 0^o$)		($\Phi \neq 0^0$)		
Reaction	Decay-channel	$\sigma_{ER}^{Cal.}$[1] (mb)	ΔR (fm)	$\sigma^{Cal.1}$ (mb)	ΔR (fm)	$\sigma^{Cal.2}$ (mb)	$\sigma_{ER}^{Expt.}$ (mb)
^{48}Ca+^{172}Yb	1n, 2n	$\sim 10^{-6}$	0.94,0.45	$\sim 10^{-6}$	0.99,0.3	$\sim 10^{-6}$	-
	3n	46.0×10^{-3}	2.0396	46.0×10^{-3}	2.004	46.0×10^{-3}	46.0×10^{-3}
	4n	1.65×10^{-4}	2.77	1.86×10^{-4}	2.78	2.34×10^{-4}	60.8×10^{-3}
	5n	0.5×10^{-3}	2.2116	0.5×10^{-3}	2.567	0.5×10^{-3}	0.5×10^{-3}
	σ_{ER}	46.66×10^{-3}		46.69×10^{-3}		46.73×10^{-3}	107.3×10^{-3}

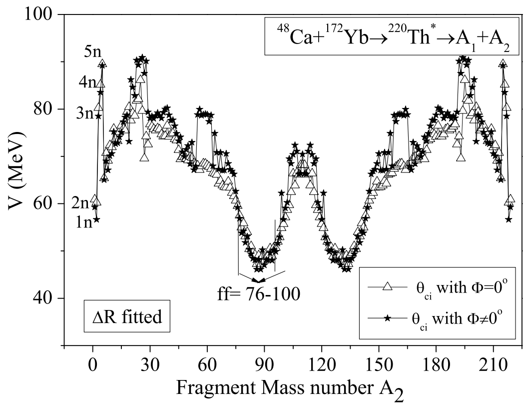

FIG. 1: The Fragmentation potentials V(A_2) for the decay of ^{220}Th*, plotted at ℓ_{max} values, for best fitted ΔR values given in Table I at E*=39.9 MeV, using "compact orientations" for multipole deformations β_{3i}-β_{4i} compared with and without Φ degree of freedom.

Calculations and Results

In this contribution we are interested in studying the role of including higher multipole deformations (β_{3i}, β_{4i}) and non-coplanar collisions ($\Phi \neq 0^o$) in the reaction mechansim and to see its effect on the non-compound nucleus contribution observed when we include only quadrupole deformations and "optimum" orientations.

Figure 1 shows the fragmentation potential for the decay of ^{220}Th* for the best fitted ΔR for the case of β_{3i}, β_{4i} without ($\Phi = 0^o$) and with Φ ($\neq 0^o$). This shows that with higher deformations and non-coplanarity the asymmetric fission mass distribution is predicted, as observed by the experiments and the fragmentation minima are almost the same but there is change in the magnitude of the minima which enhances the reaction cross section.

Table 1 shows the cross sections calculated for (β_{2i}-β_{4i}) with "compact" orientations and $\Phi = 0^o$, referred to as Cal. 1 and with $\Phi \neq 0^o$ as Cal. 2. It is observed that there is a non-compound nucleus (nCN) contribution of same order like the β_{2i} alone, and $\Phi = 0^o$. However, in earlier studies within the DCM, the nCN contribution is compensated with the inclusion of non-coplanar degree of freedom. Concluding, we see that nCN can be real or an artifact due to absence of $\Phi = 0^o$. But, in the case of ^{220}Th* the nCN contribution is still present which could not be compensated by including non-coplanarity as a degree of freedom.

References

[1] Hemdeep *et al.*, Phys. Rev. C **95**, 014609 (2017).

[2] C. C. Sahm *et al.*, Nucl. Phys. A **441**, 316 (1985).

[3] Raj K. Gupta *et al.*, Phys. Rev. C **73**, 054307 (2006).

[4] S. Chopra *et al.*, Phys. Rev. C **93**, 024603 (2016).