Study of non-compound nucleus contribution in heavy and superheavy nuclear systems formed in heavy ion reactions.

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Introduction

The advent of heavy ion reactions has facilitated to investigate the production and reaction mechanism of new heavy and superheavy nuclei via fusion reactions. Theoretically, models are advanced, e.g., by Gupta and collaborators for both the spontaneous (T=0; cluster radioactivity, the ground-state decay phenomenon) and excited (T>0) compound nuclei (CN) decays, namely the Preformed cluster model (PCM) and the Dynamical cluster-decay model (DCM) [1], respectively. In both cases, nuclear structure effects come in to play through the so-called preformation factor P_0 (the spectroscopic factor) of decay products. Using the DCM with various different nuclear interaction potentials, we have studied the hot fusion reactions for coplanar ($\Phi = 0^0$) and non-coplanar ($\Phi \neq 0^0$) nuclei. The DCM, based on the well-known quantum mechanical fragmentation theory of fission, heavy-ion reactions and exotic cluster radioactivity, successful for light to superheavy nuclei, defines the compound nucleus decay/ formation cross section for each fragmentation (A_1, A_2), for ℓ partial waves, as

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

with 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, and multipole deformations $\beta_{\lambda i}$ (λ=2,3,4; i=1,2, referring to heavy and light fragment), and orientations θ_i,Φ.

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In this work within the DCM, we have shown the importance of Φ degree-of-freedom [2] after the study of compound nucleus fusion probability (P_{CN}) and survival probability (P_{surv}). This work also shown the difference in the DCM and ℓ-summed extended Wong model using Skyrme forces. We also studied the compound nucleus survival probability P_{surv} is least understood quantity as the CN fusion probability P_{CN} [3], but quite important for the study of heavy ion reactions. Lastly, we study the SHE Z=122 with mass A=306 using the DCM, the system with available experimental data via two hot-fusion reactions ^{56}Fe+^{248}Cm and ^{64}Ni+^{242}Pu at only one excitation energy E^*=33MeV.

Calculations and Results

Firsty, we used the DCM with nuclear proximity interaction potential of Blocki et al., to study the decay of hot and rotating compound nucleus ^{105}Ag* formed in ^{12}C+^{93}Nb reaction at below barrier energies for $\Phi = 0^0$ case [4]. It is shown, for the first time, that if ER data alone is considered, fits are possible only for the 2n cross-section (σ_{2n}), predicting a rather large contribution of σ_{1n} (compared to zero for experiments), and a strong underestimation of both σ_{3n} and σ_{4n} (or σ_{4H}). However, if the fitting of both ER and IMFs (only the sum of cross-sections in this later case) is done simultaneously, interestingly σ_{1n} reduces nearly to zero, but with a large non-compound (nCN)/qf contribution. Furthermore, we looked for the effects of Φ degree-of-freedom on nCN [5]. This result became important after the study of P_{CN} and P_{surv}. For $\Phi \neq 0^0$, both P_{CN} and P_{surv} of ^{105}Ag* are the decreasing function of $E_{c.m.}$, and hence belong to the category of weakly fissioning nuclei, whereas the P_{CN} is an increasing function of $E_{c.m.}$, like for strongly fissioning superheavy nuclei.

Secondly, we studied the ^{105}Ag* within the DCM and Wong model using Skyrme forces for the nCN contribution [6]. Note that, whereas Wong determines the total fusion cross-section σ_{fusion} in terms of the barrier characteristics of the entrance channel nuclei, the DCM deals with (outgoing) decay fragments. Calculations are made for five Skyrme forces which include both old (SIII and SIV) and new (GSkI, SSk, and KDE0(v1) forces, and the results compared with the proximity potential due to Blocki et al.. Within the ℓ-summed extended-Wong model we find that with all five forces the fits to the experimental data are nice and no barrier modification is required for any choice of the Skyrme force, which means that there is no nCN content within the extended-Wong model calculations. However, the DCM calculated σ_{ER} and σ_{IMFs} do not fit the data for any Skyrme force (except for IMFs, for some forces only), and hence presents a perfect case of large nCN component in the measured cross-sections.

Next we studied P_{surv}, is also an important term for heavy ion reactions, defined as

$$P_{surv} = \frac{\sigma_{ER}}{\sigma_{CN}}, \tag{2}$$

where $\sigma_{CN} = \sigma_{ER} + \sigma_{ff}$. P_{surv} [7], determined for some sixteen "hot" fusion reactions at various incident $E_{c.m.}$ energies, covering the CN mass range of A$\sim$100 to superheavy nuclei, is analyzed on DCM for various nuclear interaction potentials like the Blocki et al. pocket formula and the Skyrme forces. Its variation with CN excitation energy E*, fissility parameter χ, CN mass number A_{CN} and Coulomb interaction parameter Z_1Z_2 is studied for both the in-plane (co-planar) and out-of-plane (non-coplanar) collisions. One of the interesting result is that the chosen 16 reactions fall in three groups of weakly fissioning, radioactive, and highly fissioning superheavy nuclei.

Finally, we studied the SHE Z=122 with mass A=306 using DCM [8], the system that has been studied experimentally via two hot-fusion reactions ^{56}Fe+^{248}Cm and ^{64}Ni+^{242}Pu , at only one E^*=33 MeV. The available experimental data for fusion-fission (ff) cross section σ_{ff} consisting of near-symmetric and symmetric fission fragments (nSF and SF)(A/2)±20 and quasi-fission (qf) cross section (σ_{qf}). We have included quadrupole (β_{2i}) deformed nuclei with "optimum" orientations ($\theta_i^{opt.}$) for "hot compact" configurations, are extended to other E^* values in the range 25-68 MeV, and for both the reactions. The interesting results of the DCM predictions are that, in agreement with experiments, the asymmetric fission maxima (in the observed ff mass region A/2±20) lie at the magic N=82, ^{136}Xe (and ^{170}Er), and the qf peaks at ^{98}Zr (and doubly magic ^{208}Pb). Further experiments are needed.

Acknowledgments

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