Projectile structure dependence of heavy-ion induced nuclear reaction dynamics in *l*-space: Role of critical angular momentum

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Introduction

Fusion reactions due to heavy nucleus-nucleus collisions range from head-on collisions up to hard-grazing peripheral collisions, in which the interacting nuclei penetrate each other to such an extent that the resulting nuclear density in the overlap region saturates. For such hard-grazing peripheral collisions, it is reasonable to assume that a strongly interacting dinuclear or composite system (CS) is formed for a defined range of impact parameters. The system may fuse completely or incompletely under the influence of complex potential of the target nucleus, and then separate into fragments. When treated quantum mechanically, one of the dependent factors of this complex potential is angular momentum (***l***) involved in heavy ion (HI) induced fusion reaction systems. Due to relatively higher mass, the heavy ions impart relatively larger angular momentum resulting in the higher energy state of the composite system. Since a large amount of angular momentum is brought into the composite system by the heavy projectile, a condition is raised where critical value of the angular momentum ($\boldsymbol{l}_{\mathbf{Critical}}$) can be reached, over which the probability of formation of a compound nucleus may disappear. So for the smaller ***l***-values ($\boldsymbol{l} \leq \boldsymbol{l}_{\mathbf{Critical}}$), complete fusion (CF) processes may occur. Beyond this limiting value ($\boldsymbol{l}_{\mathbf{Critical}}$), the increasing ***l***-values lead to different nuclear processes involving higher impact parameters following grazing trajectories in HI reactions up to the upper limit of angular momentum. This upper limit is defined as the largest angular momentum ($\boldsymbol{l}_{\mathbf{max}}$) that confines the range of associated partial waves leading to the formation of the composite system under attractive potential. It has the distance of the closest approach which is smaller than the sum of half-density radii of interacting nuclei of the colliding system. Specific localization of the various modes of reactions in the ***l***-space can be predicted by the sum-rule model [1].

According to the sum rule model, the incomplete fusion (ICF) reactions are localized in the ***l***-space above the critical angular momentum for interacting partners of the colliding system. In this situation, the projectile may break up into clusters to provide the sustainable input angular momentum carried by the composite system [2].

Formulation

The projectile can only be captured if it penetrates the region of attractive potential for the fusion reaction to occur. In this situation, a "pocket-like" structure appears due to the interplay of complex potential for lower ***l***-values in total nuclear potential-distance graph and the depth of this pocket decreases with the increasing values of ***l***. The condition of a vanishing pocket in the total potential provides the value of $\boldsymbol{l}_{\mathbf{Critical}}$ in ***l***-space, which can be calculated by the expression [1];

$$\left(l_{Critical}+\frac{1}{2}\right)^2=\frac{\mu(C_1+C_2)^3}{\hbar^2}\left[4\pi\gamma\frac{C_1C_2}{(C_1+C_2)}-\frac{Z_1Z_2e^2}{(C_1+C_2)^2}\right]$$

Where, μ is the reduced mass of the colliding system. C_1 and C_2 are the half-density radii of the two interacting nuclei. γ is the surface energy coefficient in semi-empirical mass formula. Z_1 and Z_2 are the atomic numbers of nuclei.

$$C_i = R_i\left\{1-(b^2/R_i{}^2)+....\right\}$$

$$R_i = 1.28A_i^{1/3}-0.76+0.8A_i^{-1/3}$$

$$\gamma = 0.95(1-1.78I^2)\ \text{MeV fm}^{-2},\ I=(N-Z)/A$$

(having *N*, *Z*, and *A* of composite nucleus)

Here i = 1, 2 for interacting partners, b = 1 fm [1], and R_i is the equivalent sharp radius of each partner. C_1 and C_2 are truncated with initial two terms. Further, $\boldsymbol{l}_{\mathbf{max}}$ corresponding to a peripheral collision is defined by [2];

$$l_{max} = R'\sqrt{2\mu(E-V_{CB})/\hbar^2}$$

Where, R' is the maximum distance between the interacting nuclei at which the collision leads to a reaction. V_{CB} is the Coulomb barrier of the interacting system. As $\boldsymbol{l}_{\mathbf{max}}$ varies with the incident energy of the projectile, hence the reaction cross-sections of fusion reactions can be analyzed in terms of $\boldsymbol{l}_{\mathbf{max}}$. However, $\boldsymbol{l}_{\mathbf{Critical}}$ has a specific value for specific target-projectile combination.

Analysis

In the present work, an attempt has been made to understand the nuclear reaction dynamics in ***l***-space by the analysis of reaction cross-sections of residues populated due to the interaction of considered heavy ion reaction systems: ^{14}N + ^{128}Te and ^{12}C + ^{128}Te with reference to the maximum angular momentum involved in the respective interactions. The experimental data of excitation functions has been taken from the existing literature [3, 4]. A substantial contribution of ICF has been observed in both the considered reaction systems. It is well established that in break-up fusion (BUF) kinematics, ICF corresponds to elastic breakup and partial merging of the projectile in the nuclear force field of the target nucleus.

In Fig-1, total CF cross-sections ($\sum\sigma_{CF}$), total ICF cross-sections ($\sum\sigma_{ICF}$), and total fusion cross-sections [$\sum\sigma_{TF} = \sum\sigma_{CF} + \sum\sigma_{ICF}$] have been plotted graphically as a function of l_{max}. The available experimental data for CF and ICF cross-sections has been used. It is pertinent to mention here that the total CF cross-sections have been corrected for the missing CF channels which could not be measured experimentally due to long/short half-lives of residues or other unavoidable reasons. The corrections have been done by taking the reaction cross-sections of missing CF channels from the predicted values by the statistical model based computer code PACE4 using modified set of optical model potential (OMP) parameters for target mass number $A > 100$ [5]. The code PACE4 is based on the Hauser-Feshbach (HF) theory of compound nucleus decay and calculates only the CF cross-sections. The total ICF cross-sections have been estimated by the enhancement in the available experimental cross sections of α-emitting channels in comparison to the predicted theoretical cross-sections by PACE4.

Results and Discussion

As can be seen from Fig.1, the onset of ICF is almost at $l_{Critical}$ in the case of ^{14}N + ^{128}Te system. While for ^{12}C + ^{128}Te system, there is a considerable presence of ICF well below the

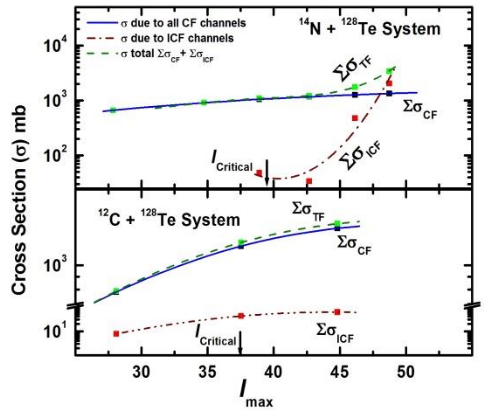

Fig-1. Reaction cross-sections of considered systems as a function of l_{max}($l_{Critical}$ is also displayed here).

$l_{Critical}$. This supports the α-cluster structure of ^{12}C projectile, which is an even-even nucleus. Moreover, the total fusion cross-sections have greater values than CF cross-sections at higher l_{max} due to the presence of ICF. Further, above $l_{Critical}$, there is a gradual increment of ICF with increasing values of l_{max} in case of ^{12}C + ^{128}Te system. Whereas, ^{14}N + ^{128}Te system reflects a sudden bump of increment for ICF along with increasing values of l_{max} after $l_{Critical}$ reflecting the non α-cluster structure of ^{14}N projectile, which is an odd-odd nuclei. It is worth noting here that the common target Tellurium-128 is a non-deformed nucleus. The observations above indicate that the nuclear structure of projectile plays an important role in deciding the dominance of certain type of reaction mechanism at different l_{max}. Moreover, there is no sharp/ threshold angular momentum cut-off for the separation of CF and ICF reactions. Details will be presented during symposium.

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