

Investigating the Low-Energy Incomplete Fusion in $^{12}\text{C}+^{193}\text{Ir}$ System

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Introduction

Low-energy heavy-ion (HI) induced nuclear reactions provide an excellent framework to study the competition between complete fusion (CF) and incomplete fusion (ICF) processes. The onset of ICF at low incident energies is strongly influenced by projectile structure and entrance channel parameters of the interacting nuclei. The present thesis reports the systematic studies on the $^{12}\text{C} + ^{193}\text{Ir}$ system in the energy range 64–84 MeV (≈ 5 –7 MeV/nucleon). The primary objective was to measure excitation functions (EFs) of evaporation residues (ERs), disentangle CF and ICF contributions by forward recoil ranges (FRRs), and examine entrance channel dependencies of ICF probability.

Experimental Details

Thin Al-backed ^{193}Ir films were fabricated using the ultra-high vacuum deposition technique at IUAC, New Delhi [1]. Irradiations with ^{12}C beams were carried out in the General Purpose Scattering Chamber using the stacked-foil activation technique. The ERs populated through xn , pxn , and αxn channels were identified using high-resolution HPGe clover detectors. The cross-sections were extracted using standard activation analysis and corrected for detector efficiency and target thickness. The theoretical analysis was performed using the PACE4 statistical model code, and data reduction procedures such as the Universal Fusion Function (UFF) and Improved Fusion Function (IFF) were employed to compare with the existing systematics.

Results and Discussion

Excitation Functions of a large number of reaction residues populated via CF and/or ICF processes in the interaction of the ^{12}C with ^{193}Ir have been measured [2]. The data analysis indicated that the ERs populated via xn/pxn channels ($^{201,200}\text{Bi}$, $^{201,200}\text{Pb}$) were found to be in good agreement with the predictions of PACE4 for the level density parameter $K = 13$, indicating their origin only through the CF process. However, a significant enhancement was observed for α -emitting channels ($^{200,199,198}\text{Tl}$, ^{196}Au) compared to PACE4 predictions, providing direct evidence of ICF.

To have a better insight into the onset of ICF and how the structure of the projectile affects the ICF dynamics, the ICF strength function (F_{ICF}) has been deduced as a function of incident energy, showing a smooth increase from 12% to 16%. F_{ICF} rises with beam energy, entrance channel mass asymmetry, Coulomb factor ($Z_P Z_T$), and neutron skin thickness, confirming the role of entrance channel dynamics.

It has been found that F_{ICF} increases with entrance channel mass asymmetry for ^{12}C , ^{13}C , ^{16}O and ^{18}O projectiles individually. Based on these observations, it can be inferred that the mass asymmetry systematics is valid only for individual projectile(s), and the projectile structure effect should be considered while interpreting the ICF data at low incident energies. Further, it has been observed that the probability of ICF is sensitive to the Coulomb factor ($Z_P Z_T$). However, α -cluster projectiles (^{12}C and ^{16}O) exhibit increasing ICF fraction trends and align on the same line, suggesting consistency in their behavior, while, non- α -cluster projectiles (^{13}C and ^{18}O) also show increasing trends in ICF,

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but separately for each projectile. Based on data analysis, it may be concluded that the structural characteristics of the projectile exert a substantial influence on ICF. Moreover, in low-energy HI reactions, ICF mainly occurs in non-central interactions; hence, neutron skin thickness may influence the probability of ICF. Neutron skin slightly reduces the Coulomb barrier due to the screening effect, which increases the attractive nuclear potential. The probability of ICF is found to increase with neutron skin thickness for individual projectiles, indicating larger ICF probability for neutron-rich, heavy mass target nuclei. From the systematics, it has been found that the probability of ICF is higher for reactions involving ^{12}C projectile than those involving ^{13}C projectile, pointing towards the effect of the Q_α value of the projectile. The projectile with a more negative Q_α value will have fewer ICF contributions, consistent with Q_α value systematics [3].

With a view to disentangle the CF and ICF reactions in the present work, the FRRs of reaction residues viz., $^{200,199,198}\text{Tl}$ ($\alpha n, \alpha 2n, \alpha 3n$) and ^{196}Au ($2\alpha n$) populated in the interaction of ^{12}C with ^{193}Ir target have been measured at energy 83.99 MeV. A significant contribution from ICF reactions has been observed in almost all the α -emitting channels. It strongly reveals a transfer of partial momentum from the projectile to the target nucleus in the case of α -emitting channels associated with ICF reactions. The different partial LMT components correspond to the breakup of ^{12}C with the target nucleus if ^{12}C breaks up into $^8\text{Be} + \alpha$. FRRs confirmed partial momentum transfer in α -emitting channels, supporting ICF origin [4].

The fusion cross-section data of the present system $^{12}\text{C} + ^{193}\text{Ir}$ have been reduced to eliminate differences that may arise due to the size and charge of the interacting nuclear entities. Analysis within the framework of UFF indicates that fusion is suppressed by $\approx 12\%$ for the $^{12}\text{C} + ^{193}\text{Ir}$ system. The suppression of experimental fusion functions concerning the UFF or the probability of ICF is estimated to be influenced by the α breakup threshold energy of the projectile. The projectile

with a more negative Q_α value is likely to give rise to less fusion suppression and vice versa. The magnitude of suppression for the present system has been found to align with the empirical relation obtained by Wang et al. [5] after slight modifications to the parameters. This observation further suggests that the breakup threshold energy affects the projectile breakup and, hence, the fusion cross-section. Moreover, the experimental fusion cross-section data for various systems, including the $^{12}\text{C} + ^{193}\text{Ir}$ system, were plotted alongside the IFF. A suppression of 6% has been observed for $^{12}\text{C} + ^{193}\text{Ir}$ system w.r.t. Classical Fusion Line (CFL). The reduced data points for different tightly bound projectile-target combinations closely align with the CFL, reflecting that nuclear structure properties have minimal influence at above-barrier energies.

This study provides new experimental data and insights into the role of projectile structure and entrance channel effects in ICF at near-barrier energies. The results contribute to global efforts to understand the interplay of CF and ICF in low-energy HI collisions.

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