Investigation of Incomplete Fusion events: Recent Results

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Abstract. The dynamics of incomplete fusion processes has been extensively investigated and is found to compete with complete fusion at low incident energies (i.e. < 7.0 MeV/A). Recent reports suggest that the probability of incomplete fusion depends on $Q_{\alpha}$ of the projectile, and found to be originated from the high input angular momentum provided into the system due to non-central collisions. Apart from the well documented existence of low energy incomplete fusion, a strong contradiction on previously established mass-asymmetry systematics has been noticed recently. It has been found that the incomplete fusion fraction increases with entrance channel mass-asymmetry for the individual projectiles. Further, a strong dependence of incomplete fusion on the Coulomb effect ($Z_PZ_T$) has been observed and is found to increase linearly with $Z_PZ_T$, a significantly important approach to understand the breakup fusion reactions. For better insights into the onset and strength of incomplete fusion in terms of various entrance channel parameters and to understand the role of high angular momenta in the onset of incomplete fusion, a quality data have been obtained in a variety of experiments performed at the Inter-University Accelerator Center (IUAC), New Delhi, India. Some of the recent results are presented in this paper, conclusively demonstrating the effect of entrance channel parameters on the onset and strength of incomplete fusion, and the usefulness of incomplete fusion to populate high-spin states in final reaction products.

1. Introduction
Fusion reactions between heavy-ions constitutes an important field of research in low energy nuclear physics with stable nuclei and are likely to become more important when radioactive beams of high intensity will be available [1, 2, 3, 4, 5]. At low energies, starting from the Coulomb barrier to 7.0 MeV/A, the study of reaction mechanism concerning the transition between complete fusion (CF) and incomplete fusion (ICF) processes is important in the view of understanding the interplay between the two dominant modes of the nuclear interaction. In the later reaction processes, partial fusion of the projectile with the target nucleus takes place, leading to the formation of a “hot” metastable incompletely fused composite system
Figure 1. (Color Online) (a) Experimentally measured total CF cross section (filled bullets), total $\alpha$’s cross section (filled triangles). A comparison with PACE4 ($k = 8$) channel has also been shown. (b) The values of $F_{ICF}$ for different projectile-target combinations as a function of entrance channel mass-asymmetry ($\mu_A$) at a constant relative velocity (i.e., $v_{rel} \approx 0.053c$). The lines drawn through the data points guide the eyes for individual ($^{12}$C, $^{14}$N, $^{16}$O) projectiles.

with less mass, charge, and excitation energy as compared to the CF population, where the entire projectile merges with the target nucleus [6, 7, 8, 9]. Though several models and theories [10, 11, 12, 13] are available to understand the dynamics of ICF processes, but no satisfactory explanations of ICF data could be made at low energies. In some recent reports, a large fraction of ICF has been observed at these energies [14, 15, 16, 17, 18, 19], which triggered the resurgent interest to understand the low energy ICF reaction dynamics.

In the present work, the effect of projectile structure (in terms of the $Q_\alpha$ value and projectile dependent mass-asymmetry), and the charge dependence (i.e., the product of the projectile atomic number ($Z_P$) and the target atomic number ($Z_T$)) on the onset and strength of ICF have been studied via excitation function measurements (EFs). On the other hand, the usefulness of ICF as a spectroscopic tool to populate high spin states in the final reaction products has been studied via spin distribution measurements (SDs). The data were obtained using 15 UD Pelletron at the Inter University Accelerator Center (IUAC), New Delhi, India. Irradiations for the EFs were performed in the General Purpose Scattering Chamber [20]. After the irradiations, the radioactivity produced in each target catcher assemblies was measured offline for several days with two high resolution High Purity Germanium (HPGe) detectors. On the other hand, an online experiment to measure the SDs associated to the reaction residues was performed in the Gamma Detector Array-Charge Particle detector Array [21, 22]. The prompt $\gamma$-rays were recorded with 12 Compton suppressed HPGe detectors mounted at angles $45^0$, $99^0$, $153^0$ with respect to the beam axis, and were in coincidence with the particles & $\alpha$’s detected with 14 Phoswich detectors housed in a 14 cm diameter scattering chamber. Details of the experiments (offline and online) can be found elsewhere [23, 24].

The present paper is organized as follows: Interpretation of fusion excitation functions in context of the statistical model code PACE4 [25] is given in Section 2, while Section 3 deals with the spin distribution measurements (SDs) using a particle-gamma coincidence technique,
and to obtain the correlation with the driving angular momentum involved in the ICF channels. Section 4 deals with the summary and conclusions of the present work.

2. Excitation Function Measurements: Strength and onset of incomplete fusion

The fraction of ICF (F_{ICF}) has been measured for several systems [7, 8, 15, 17, 18, 26] using the novel activation technique followed by offline γ-ray spectroscopy. It may be mentioned that the F_{ICF} has been deduced from the analysis of experimental excitation functions in the framework of statistical model code PACE4. The detailed discussion on data reduction procedure and obtained results can be found elsewhere [15, 26]. As a representative case, the sum of all experimentally identified ICF-channels (filled triangles) is plotted with respect to bombarding energy along with the sum of all CF-channels (solid circles) in Fig. 1(a) for the {^{14}\text{N}+^{169}\text{Tm}} system. The Fig. 1(a) shows the sum of cross-sections for the xn and pxn reactions (solid circles) extracted experimentally and matches satisfactorily with the predictions of PACE4 using the level density parameter constant ‘K’=8 (solid line). It may be relevant to mention that the code PACE4 takes into account the excitation energy dependence of the level density parameter (a=A/K) using the prescription of Kataria, Ramamurthy, and Kapoor [27]. In order to trace the suitable value of ‘a’, to reproduce the experimental fusion EFs, the values of ‘K’ were varied from 8 to 12. It has been observed that the value ‘K’=8 satisfactorily reproduces experimental fusion EFs and the same is highlighted with solid line (See Fig. 1(a)). The value of ‘K’=8 was also suggested by Gilbert and Cameron [28] at the studied energy range in this mass region. Further, the sum of all identified α-channels cross-sections (filled triangles) is compared with the theoretical α-channels cross-sections (dotted line) calculated using PACE4 at the same value of ‘K’ and the same is presented in Fig. 1(a). As can be seen from the figure, the experimentally deduced α’s are higher when compared to corresponding PACE4 predictions (Σσ_{α’s}^{PACE4}). This enhancement over the theoretical prediction may be attributed due to the contribution from ICF. Further, an attempt has been made to deduce experimental ICF cross section (Σσ_{ICF}^{exp}) by subtracting the experimentally deduced α’s with corresponding PACE4 predictions (dashed line). Moreover, for better insights into the onset and strength of ICF, the percentage fraction of ICF (i.e. F_{ICF}) is derived using following expression;

\[
F_{ICF} = \frac{\Sigma \sigma_{ICF}^{exp}}{\Sigma \sigma_{TF}} \times 100
\]

where, Σσ_{ICF}^{exp} and Σσ_{TF} are experimental ICF and total fusion cross-sections, respectively. In order to see the dependence of ICF on entrance channel mass asymmetry \(\mu_A = \alpha T/(\alpha T + \alpha P)\), where \(\alpha P\) is the atomic mass number of the projectile and \(\alpha T\) is the atomic mass number of the target nucleus), the present results are analyzed within the framework of Morgensterns systematics [29, 30]. According to Morgensterns mass-asymmetry systematics, ICF contributes significantly above relative velocity \(v_{rel} (= 0.06 \text{ (6 \% of c)}\) of the projectile, and the fraction of ICF (F_{ICF}) should increase with the mass-asymmetry (\(\mu_A\)) of the system. The F_{ICF} for our recently performed experiment \({^{14}\text{N}+^{169}\text{Tm system}}\) [26] is compared with the available nearby systems [see references in [26]] and are plotted in Fig. 1(b) at a constant relative velocity \(v_{rel} \approx 0.053c\). Lines through the data points are drawn to guide the eyes for individual projectiles. As can be seen from this figure, the variation of F_{ICF} does not increases with the \(\mu_A\) of the system, however, the value of F_{ICF} increases with \(\mu_A\) for individual projectiles. One of the reasons for such behavior can be understood by considering that, for a given projectile, as the mass asymmetry increases the Coulomb effect (repulsion) also increases, giving rise to a larger breakup probability. In order to display the charge dependence of the ICF strength function, the F_{ICF} values are plotted in Fig. 2(a) as a function of \(Z_P Z_T\) of the system along with F_{ICF} of other systems available in the literature [26, references therein] at the same \(v_{rel}\) (i.e. \(\approx 0.053c\)). As can be seen from the figure, the F_{ICF} follows almost a linear growth as the charge product
3. Spin Distribution Measurements: localization of the \( \ell \) window

In head-on or near head-on heavy ion collisions, the reacting nuclei may lead to the formation of a compound nucleus (CN), where the driving input angular momentum ‘\( \ell \)’ associated can reach...
Figure 3. (Color Online) Experimentally generated spin-distributions of $\alpha n$ and 4n-channels. Lines and curves are the best fit to the experimental data points [40]. Fitting and normalization procedures are explained in the [41].

As a representative case, the spin-distributions for the 4n and $\alpha n$ channels, that is, $^{171}$Ta(4n) identified from singles spectra, and $^{170}$Lu($\alpha n$) identified from fast-$\alpha$-gated-$\gamma$ spectra detected in the forward cone are plotted in Fig. 3. As can be seen from this figure, the trend of the yield distribution for the $\alpha$-emitting channel identified from forward $\alpha$-gated-$\gamma$ spectra is distinctly different from that of the 4n-channel identified from singles data. A gradual steep rise in yield for 4n-channel towards the band head indicates continuous spin population for a broad spin range during the de-excitation. However, in case of $\alpha n$-channel, the intensity increases up to a value of observed spin ($J_{obs}$) $\approx 10 \hbar$ and then shows a constant behavior towards the band head. Thus, the constant behavior from 8 $\hbar$ to 2$\hbar$, reveals the hindrance in the population of low lying states in ICF processes. Moreover, the spin-distribution patterns of neutron and $\alpha$-emitting channels clearly suggest reaction dependent de-excitation patterns. In order to reinstate distinct nature of de-excitation pattern observed in the Fig. 3, the spin distributions for the $^{168}$Lu residue identified from forward $\alpha$-gated-$\gamma$ spectra (F) and backward $\alpha$-gated-$\gamma$ spectra (B) are shown in Fig. 4 (a and b) for the projectile energies, $E_{lab} = 83.5 \pm 1.5$, 88.5 $\pm$ 1.5, 93.5 $\pm$ 1.5 and 97.6 $\pm$ 1.4 MeV, respectively. As can be observed from Fig. 4, the trend of spin-distributions...
Figure 4. (Color Online) Experimentally generated spin-distributions of (a) $\alpha$3n-B, and (b) $\alpha$3n-F channels. Lines and curves are the best fit to the experimental data points [38].

Figure 5. (Color Online) The value of mean input angular momenta $<\ell>$ associated with the production of different isotopes in $^{16}$O+$^{159}$Tb system at studied energies. Lines and curves through data points are drawn to guide the eyes.

for $^{168}$Lu-B(complete fusion) and $^{168}$Lu-F (incomplete fusion) is visibly different, and follow the same behavior as that of 4n- and $\alpha$n-channels, respectively. It may be mentioned the for $\alpha$n-xn-F-channels (ICF residues), the intensity appears to be almost constant up to a certain value of $J_{obs}$, and varies with the incident projectile energies, which then decreases towards band head. From the experimental observations it may be concluded in case of ICF, population of low lying states or lower levels are strongly hindered and there is absence of feeding of $\gamma$’s from higher levels.
In order to understand the usefulness of ICF as a tool to populate high spin states in the final reaction products, the values of $\ell$ involved in CF- and ICF-channels have been deduced from the analysis of experimental spin-distributions [38, 24] and are plotted in Fig. 5 as a function of incident projectile energy. As indicated in this figure, the $<\ell>$ values involved in complete fusion ($xn/\alpha xn$) and incomplete fusion ($\alpha xn$) channels are found to be $\approx 6 \hbar$ and $\approx 11 \hbar$ respectively, at projectile energy $\approx 83.5 \pm 1.5$ MeV, and increases linearly for higher energies. On comparing the $<\ell>$ values involved in the ICF ($\approx 11 \hbar$) at the lowest projectile energy is found to be $38\%$ than that involved in the CF channels ($\approx 8 \hbar$) at the highest experiential incident laboratory energy. This clearly demonstrates the involvement of higher $\ell$-values in the production of incomplete channels which may lead to the population of higher spin-states in the final reaction products which may not be possible otherwise.

4. Summary and Conclusions

The present paper gives the experimental results for the excitation function and particle-γ coincidence experiments performed using 15UD pelletron facility at the IUAC, New Delhi, India. In case of excitation function experiments, the cross sections of $\alpha$ exit channels were found to be enhanced when compared with the theoretical model using code PACE4. A comparison of $F_{\text{ICF}}$ for different projectile and on the same target ($^{169}\text{Tm}$) combinations displays higher ICF probability for the $^{16}\text{O}+^{169}\text{Tm}$ system, though it is a less mass-asymmetric system than $^{12}\text{C}$, $^{14}\text{N}+^{169}\text{Tm}$ systems (see Fig. 1(b)). Morgensterns mass-asymmetry systematics do not explain the experimental data of eight nearby systems as a whole, however, the value of $F_{\text{ICF}}$ is found to increase with entrance channel mass-asymmetry $\mu_A$ for individual projectiles. Further, a strong dependence of the incomplete fusion strength function ($F_{\text{ICF}}$) on the Coulomb effect, i.e., $Z_P/Z_T$ was observed on comparing systems available in literature. Moreover, the effect of $Q_\alpha$ on ICF fraction has been observed for strongly bound projectiles. The $F_{\text{ICF}}$ has been found to decrease for large negative $Q_\alpha$ of the projectiles. If confirmed for other projectile-target combinations, this may provide an important input to understand the complex ICF dynamics at low incident energies.

In the case of spin distributions, residues populated through the ICF routes are found to be originated from the narrow spin population, localized near and/or above to the critical angular momentum for CF to occur, where a given direct-α-fragment is emitted to release excess driving angular momenta. This reveals a competition from successively opened ICF channels for each value of $\ell$ above the $\ell_{\text{crit}}$ for normal fusion (CF). Further, results based on spins reveals that the high $\ell$-values associated with peripheral interactions contribute to open up direct-α-channels.

In conclusion, to achieve better understanding of the dependence of low-energy incomplete fusion reaction dynamics on various entrance channel parameters, more precise and diversified data is required.

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