Understanding the onset of incomplete fusion

Pushpendra P. Singh¹, Abhishek Yadav², Vijay R. Sharma², D. P. Singh², R. Kumar³, R. P. Singh³, S. Muralithar³, B. P. Singh², R. K. Bhownik⁴, R. Prasad², and the AMU-IUAC collaboration

¹Department of Physics, Indian Institute of Technology Ropar, Punjab - 140 001, India
²Accelerator Laboratory, Department of Physics, A. M. University, Aligarh-202 002, India
³NP-Group, Inter-University Accelerator Center, New Delhi-110 067, India
⁴Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700 064, India

E-mail: pps@iitrpr.ac.in

Abstract. The entrance channel effect on the onset and strength of incomplete fusion (icf) has been studied in the present work. Several inclusive experiments have been performed to measure the icf strength function in \( ^{12}C, ^{16}O+^{169}Tm \) systems at near and above barrier energies. Data obtained in these experiments suggest the existence of icf even at slightly above barrier energies where complete fusion (cf) is supposed to be the sole contributor, and conclusively demonstrate strong projectile structure and energy dependence of icf. The incomplete fusion strength functions for \( ^{16}O, ^{12}, ^{13}C+^{159}Tb \) and \( ^{16}O, ^{12}, ^{13}C+^{181}Ta \) systems are analyzed as a function of projectile \( \alpha \)-Q-value at a constant \( \nu_{rel} = 0.053c \). It has been found that one neutron (1n) excess projectile \( ^{13}C \) (as compared to \( ^{12}C \)) results in less incomplete fusion contribution due to its relatively large negative \( \alpha \)-Q-value. In order to understand the onset of icf at such low energies, the driving input angular momenta (\( \ell \)) involved in the production of different evaporation residues have been deduced from the analysis of experimentally measured spin-distributions for the same projectile-target combinations at the same incident energies. Higher \( \ell \)-values, imparted into the system in non-central interactions, are found to be responsible for low energy icf. The icf-\( xn/2xn \) channels display involvement of higher \( \ell \)-values than that observed in cf-\( xn/pxn/\alpha xn/2\alpha xn \) channels at the very same projectile energies. It has been observed that the mean value of \( \ell \) increases with successively opened icf channels and incident energy.

1. Introduction

Incomplete fusion (icf) - where only a part of projectile fuses with target nucleus - in light heavy-ion (hi) induced reactions has recently been identified as a process of great significance even at slightly above barrier energies. According to the conventional picture of fusion, the interaction of two heavy nuclei at energies near and above the Coulomb barrier leads to a completely fused composite system. In this case, entire mass and charge of the interacting partners amalgamate with all nucleonic degrees of freedom to form a fully equilibrated compound nucleus which may eventually decay via light nuclear particles and/or characteristic \( \gamma \)-rays. This mode of reaction is termed as complete fusion (cf) [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12].

Recent studies, however, showed strong influence of icf on cf at low incident energies, i.e., \( E_{lab}\approx 3-7 \) MeV/nucleon [13, 14]. Unexpected show up of (icf) at slightly above barrier energies has been justified as the natural extension of fusion due to excess input angular momenta (\( \ell \)) imparted into the system in non-central interactions [4]. The fact that the cf and icf
events can be disentangled in terms of input angular momenta ($\ell$-values) and on the basis of degree of linear momentum transfer ($\rho_{LMTR}$) from projectile to target nucleus [11, 15, 16]. The interaction trajectories associated with $\ell$-values $\rightarrow \ell \leq \ell_{crit}$ lead to CF events with predefined mass $A$, charge $Z$ and recoil velocity $v_{recoil}$. However, for $\ell$-values $\rightarrow \ell \geq \ell_{crit}$, the interaction $\ell$-balance inhibits fusion of entire projectile with target nucleus [4]. As a consequence, the incident projectile breaks up into its constituents to provide sustainable input angular momenta. A part of projectile fuses with target nucleus which leads to an incompletely fused composite system with relatively less $A$, $Z$ and $v_{recoil}$ as compared to CF events, and direct projectile-like-fragments mainly centered in forward cone.

The dynamics of ICF have been extensively investigated and several theoretical models have been proposed, see ref.[11]. Morgenstern et al. [17] correlated the fraction of ICF with $\mu_A$, which suggests large ICF fraction for more mass-asymmetric system at a constant relative velocity ($v_{rel} = \sqrt{2(E_{cm} - V_b)/\mu/c}$). The peripheral nature of ICF has been emphasized by Inamura et al.[18]. However, the studies on ICF dynamics by Tserruya et al.[19] revealed the existence of both CF and ICF below and above the value of $\ell_{crit}$. Despite a variety of existing studies (see ref.[12] for detail), the dynamics of ICF at low incident energies is still not fairly understood, thus continues to be an active area of investigations.

In the present work, the onset and strength of ICF have been studied in terms of (i) projectile energy ($E_{lab}$), (ii) mass-asymmetry ($\mu_A = A_T/A_{T+P}$) of interacting partners, (iii) projectile $\alpha$-$Q$-value, and (iv) input $\ell$-values to better understand the ICF dynamics. Experiments have been performed at the Inter-university Accelerator Center (IUAC), New Delhi. The percentage fraction of ICF, deduced from the experimental excitation functions of individual reaction residues in different projectile-target combinations, shows strong dependence on $E_{lab}$, $\alpha$-$Q$-value and $\mu_A$. Two particle-$\gamma$-coincidence experiments have been performed for the same projectile target combinations to understand the onset of ICF at slightly above barrier energies. The spin-distributions (SDs) of individual reaction residues have been measured. Experimental results from nearly systems are compared to display the entrance channel effect on ICF dynamics. The experimental and data reduction methodology are presented in section II. The finding of the present work and their interpretations in context of statistical model code PACE4 are given in section III, where the influence of ICF on CF and its dependencies on various entrance channel parameters are demonstrated. Section IV deals with the summary and conclusions of the present work.

2. Experimental and data reduction methodology

Experiments have been performed at IUAC New Delhi using general purpose scattering chamber (GPSC) and gamma detector array (GDA) coupled with charged particle detector array (CPDA) setups. The methodology and experimental setups have been discussed in refs.[10, 11, 12, 13, 14]. However, a brief account of experimental conditions is given here for the ready reference.

The EFS of individual reaction residues populated via CF and/or ICF in $^{12}\text{C},^{16}\text{O}+^{169}\text{Tm}$ systems have been measured using stacked foil activation technique [10, 11, 12, 13, 14]. A stack of 3 target foils of natural $^{169}\text{Tm}$ (of abundance = 100%, and thickness $t_m$ $\approx$ 1-1.8 mg.cm$^{-2}$) each backed by Al-foils of appropriate thicknesses to stop the most energetic recoiling products was bombarded in GPSC with $^{12}\text{C}$ and $^{16}\text{O}$ beams of energy range $\approx$ 4-7 MeV/nucleon with beam current $\approx$ 20-30 nA. The evaporation residues (ERS) produced during the irradiations were counted off-line with two pre-calibrated HPGe detectors. The ERS have been identified by their characteristic $\gamma$-lines and confirmed in their decay-curve analysis. A part of $\gamma$-ray spectra obtained at $E_{lab} = 89.3$ MeV in $^{12}\text{C}+^{169}\text{Tm}$ system is shown in Fig.1(a). Some of the peaks corresponding to different reaction residues are marked. Decay curve of $^{177}\text{Re}$($t_{1/2} = 14$ min) which is obtained by following 197 keV $\gamma$-line at increasing decay time is drawn in Fig.1(b). The production cross-sections ($\sigma_r(E)$) of ERS have been calculated using standard formulation [12],
The overall error in $\sigma_r$ is estimated to be $\approx 14\%$, excluding the uncertainty in branching ratios, decay constant, etc. Details of the error estimation and causing factors are given in ref.[12].

Figure 1. (a) A part of $\gamma$-ray spectra obtained at $E_{lab} = 89.3$ MeV in $^{12}$C+$^{169}$Tm system. Some of the peaks corresponding to different reaction residues are marked. (b) Decay curve of $^{177}$Re($t_{1/2} = 14$ min) which is obtained by following 197 keV $\gamma$-line at increasing decay time.

Aiming to probe the role of high $\ell$-values in the onset of ICF, the spin-distributions (SDs) of xn/pxn/$\alpha$xn/2$\alpha$xn-channels have been measured in $^{12}$C,$^{16}$O+$^{169}$Tm systems at energies $\approx 4$-7 MeV/nucleon using particle-$\gamma$ coincidence technique [4]. Coincidences between particles($Z=1,2$) and prompt-$\gamma$s have been demanded using GDA and CPDA setups. Self-supporting $^{169}$Tm (abundance = 100%) target of thickness $\approx 1$mg/cm$^2$ has been bombarded with $^{12}$C+$^{5}$($E\approx 54$-90MeV) and $^{16}$O+$^{7}$($E\approx 90$MeV) beams. It may be pointed out that the forward cone ($\theta=10^\circ - 60^\circ$) detectors are supposed to detect both; ($i$) CF $\alpha$-component of energy $E_{\alpha - evaporation}=18$ MeV, and ($ii$) ICF direct-$\alpha$-component belongs to the same velocity as that of incident projectile, e.g., $E_{\alpha - direct}=22.5$ MeV in case of 90MeV $^{16}$O beam. In order to completely remove $\alpha - evaporation$ component detected in the forward cone, an Al-absorber of appropriate thickness has been kept on forward ($10^\circ - 60^\circ$) CPD’s so that only direct $-\alpha$ component of energy $E \geq 18$ MeV can be detected. The prompt $\gamma$-ray spectra have been recorded for different gating conditions, namely; $\alpha$ and 2$\alpha$ detected in the backward(B), forward(F) and $90^\circ$-angular zones. The SDs of xn-channels have been drawn by looking into the singles spectra. For the identification of prn-channels, backward(B)-$\alpha$-gated spectra has been subtracted from backward(B)-particles($Z=1,2$)-gated spectra. However, $\alpha$xn/2$\alpha$xn(CN-$\alpha$)-channels produced via CF have been identified from the backward(B)-$\alpha$-gated spectra. Further, the direct-$\alpha$-particles associated with ICF are expected to be emitted in forward cone. The $\alpha$n/2$\alpha$n(Direct-$\alpha$)-channels produced via ICF have been identified from forward(F)-$\alpha$-gated spectra. The intensity and area under the photo-peak of the characteristic prompt $\gamma$-rays assigned to the particular reaction products were used to determine the relative production yield [4].

3. Entrance channel dependence of ICF: findings and interpretations
The effect of various entrance channel parameters, namely; ($i$) projectile energy, ($ii$) entrance channel mass-asymmetry of interacting p($\mu_A$), ($c$) $\alpha$-Q-value, and ($d$) input $\ell$-values, on the
onset and strength of ICF have been systematically investigated in the present work. Finding of different experiments and their interpretations are presented in the following subsections.

3.1. Energy dependence of ICF

The experimental EFs of individual (ERs) have been analyzed in the framework of statistical model code PACE4 to probe the energy dependence of ICF. Details of code PACE4 can be found in ref.[12]. The value of level density parameter (a=A/K) is an important input parameter in this code which can be tuned to fit the experimental data. Different values of ‘a’ from A/10 - A/8 MeV\(^{-1}\) have been tested to reproduce experimental EFs. The ERs populated via xn/pxn-channels have been found to be in good agreement with that estimated via PACE4. However, the experimental EFs of α-emitting channels have been observed to be significantly enhanced as compared to the PACE4 predictions, indicating the existence of ICF. The experimental EFs of α-emitting channels are subtracted from the theoretical ones (\(\sigma_{ICF} = \sigma_{exp} - \sigma_{PACE4}\)) to get ICF contribution [11]. The percentage fraction of ICF (F\(_{ICF}\)) has been deduced and is plotted as a function of projectile relative velocity (\(v_{rel} = \sqrt{2(Ecm - Vb)/\mu c}\)) for \(^{12}\)C,\(^{16}\)O\(^{+169}\)Tm and \(^{12}\)C\(^{+159}\)Tb systems in Fig.2(a), i.e., termed as ICF strength function.

![Figure 2](image_url)

**Figure 2.** (a) The percentage fraction of ICF as a function of projectile relative velocity (\(v_{rel}\)) for \(^{12}\)C,\(^{16}\)O\(^{+169}\)Tm and \(^{12}\)C\(^{+159}\)Tb systems, (b) the percentage fraction of ICF as a function of \(\mu A\) for 11 projectile-target combinations at a constant value of \(v_{rel} \approx 0.053\).

The F\(_{ICF}\) defines empirical probability of ICF at different values of \(v_{rel}\). As shown in this figure, the F\(_{ICF}\) increases linearly with normalized projectile energies (i.e., \(v_{rel}\)). According to Morgenstern’s systematics [17], ICF contributes significantly above \(v_{rel} \approx 0.06\) (6 % speed of light). As indicated in this figure, the values of \(v_{rel}\) are in the range from \(\approx 0.027\) (2.7 % of c) to \(\approx 0.084\) (8.4 % of c) for \(^{12}\)C, and from \(\approx 0.014\) (1.4 % of c) to \(\approx 0.053\) (5.3 % of c) for \(^{16}\)O. Therefore, no significant ICF contribution is expected at the given values of \(v_{rel}\). However, the results presented in Fig.2(a) clearly demonstrate the onset of ICF at relatively lower value of \(v_{rel}\) i.e., \(\approx 0.027\) (F\(_{ICF}\) \(\approx 7\) %) in \(^{12}\)C\(^{+169}\)Tm system, and at \(\approx 0.014\) (F\(_{ICF}\) \(\approx 10\) %) in \(^{16}\)O\(^{+169}\)Tm system. In both cases, the observed value of F\(_{ICF}\) is significant at well below the proposed onset value of \(v_{rel}\) (i.e., 6 % of c). Further, as shown in Fig.2(a), the value of F\(_{ICF}\) for \(^{12}\)C-projectile is lower than \(^{16}\)O-projectile for the entire measured energy range. The difference in F\(_{ICF}\) for two
systems ($^{12}\text{C}, ^{16}\text{O}+^{169}\text{Tm}$) can be seen clearly which points towards projectile structure and/or $\mu_A$ effect on ICF.

3.2. Projectile dependence of ICF

The percentage fraction of ICF has been deduced and plotted as a function of $\mu_A$ for 11 projectile-target combinations ($^{12}\text{C}+^{128}\text{Te}, ^{165}\text{Ho}, ^{169}\text{Tm}$ and $^{16}\text{O}+^{103}\text{Rh}, ^{159}\text{Tb}, ^{169}\text{Tm}$) at a constant value of $v_{rel} \approx 0.053$ in Fig.2(a) to understand projectile structure and/or $\mu_A$ dependence of ICF. It may be pointed out that both $^{12}\text{C}$ and $^{16}\text{O}$ are $\alpha$-cluster nuclei, which may break up into several combinations of $\alpha$-clusters. The probability of breakup increases with input $\ell$-values imparted into system in peripheral interactions [4]. Some of the breakup combinations which have been observed in previous studies are: (a) $^{12}\text{C} \rightarrow ^8\text{Be}+^4\text{He}(\alpha)$ and/or three $\alpha$ fragments, and (b) $^{16}\text{O} \rightarrow ^{12}\text{C}+^4\text{He}, ^8\text{Be}+^8\text{Be}$ and/or four $\alpha$ fragments. One or a group of fragments may fuse with target nucleus to form an incompletely fused composite system. The overlap between the interacting nuclei and the transformed mass depends on the number of nucleon occupying the overlapping volume. As such, $^{16}\text{O}$ may open up more ICF channels as compared to $^{12}\text{C}$ induced reactions. As can be seen from Fig.2(b), the Morgenstern’s systematics does not explain the variation of $F_{ICF}$ with $\mu_A$ for given systems. However, the value of $F_{ICF}$ increases with $\mu_A$ individually for $^{16}\text{O}, ^{12}\text{C}$ and $^{14}\text{N}$ projectiles. It is interesting to note that the $^{12}\text{C}+^{169}\text{Tm}$ system is a more mass asymmetric ($\mu_A = 0.9337$) system than $^{16}\text{O}+^{169}\text{Tm}$ system ($\mu_A = 0.9135$), but the value of $F_{ICF}$ is $\approx 18\%$ higher than that observed for $^{12}\text{C}+^{169}\text{Tm}$ system. The aforementioned observations based on 11 projectile-target combinations strongly contradict Morgenstern’s mass-asymmetry systematics, and suggest strong projectile dependence of ICF.

![Figure 3](image-url)

**Figure 3.** The values of $F_{ICF}$ for $^{16}\text{O}, ^{12,13}\text{C}+^{159}\text{Tb}$ and $^{16}\text{O}, ^{12,13}\text{C}+^{181}\text{Ta}$ systems are plotted as a function of projectile $\alpha$-Q-value at a constant $v_{rel} = 0.053c$.

3.3. $\alpha$-Q-value dependence of ICF

For better insight into the onset of ICF, the percentage fraction of ICF is analyzed in terms of projectile $\alpha$-Q-value for 6 projectile-target combinations. The value of $F_{ICF}$ is plotted as a
function of $Q_\alpha$ in Fig.3(a-b) at a constant $\nu_{rel} = 0.053c$. As shown in this figure, the probability of ICF for the $^{13}\text{C}$ projectile is noticeably smaller than that for the $^{12}\text{C}$ projectile. The strikingly different ICF fractions for $^{13}\text{C}$ and $^{12}\text{C}$ induced reactions point towards the projectile structure effect. It may be pointed out that $^{12}\text{C}$ is a well known $\alpha$-cluster nucleus with $Q_\alpha =-7.37 \text{ MeV}$. However, $^{13}\text{C}$ has a larger $Q_\alpha$-value ($=-10.64 \text{ MeV}$) than $^{12}\text{C}$. The higher $Q_\alpha$-value for $^{13}\text{C}$ translates into the smaller breakup probability into constituent $\alpha$-clusters, resulting in a smaller ICF fraction than that found in $^{12}\text{C}$ induced reactions. It is evident in Fig.3(a-b) that the probability of ICF is found to be less for larger negative $Q_\alpha$-value projectiles. For example, the value of $F_{\text{ICF}}$ for the $^{16}\text{O}(Q_\alpha =7.16 \text{ MeV}) +^{159}\text{Tb}$ system is found to be 19% which is reduced to only 3% for the $^{13}\text{C}(Q_\alpha =-10.64 \text{ MeV}) +^{159}\text{Tb}$ system. The same systematics was followed for the $^{181}\text{Ta}$ target. Hence, from the data presented in this figure, it can be inferred that the $Q_\alpha$-value is an important entrance channel parameter which essentially dictates the probability of ICF.

3.4. Angular momentum dependence of ICF

The fact that the relative number of statistical and yrast-like transitions depend on entry state angular momenta ($\ell$) and the excitation energy ($E^*$). The CF residues are formed at high $E^*$ and at low $\ell$ leading to more statistical transitions, where ‘yrast’ states are expected to be fed by statistical $\gamma$-transitions. However, the ICF residues achieve low $E^*$ (due to the involvement of partial degrees of excitations) and high $\ell$ (relatively higher values of impact parameters contribute to the high spin states) at a given projectile energy. In such a case, number of ‘yrast’-like transitions are much larger than that of statistical ones, where less or no feeding is expected. As a result, the spin-distributions of CF and ICF residues are expected to be entirely different in nature and can be used as a sensitive tool to probe the mode of reaction by looking into the entry state spin population. In order to probe the role of high $\ell$-values in the production of ICF residues, the spin-distributions of various CF and ICF channels have been measured [4].

![Figure 4](image-url)

**Figure 4.** (a) the spin-distributions of $x_n/\alpha x_n/2\alpha x_n$-channels populated via CF and ICF in $^{12}\text{C},^{16}\text{O}+^{159}\text{Tm}$ systems. The nomenclature used in this figure is explained in the text, and the lines & curves are best fit to the data points. (b) mean ‘$\ell$-values’ involved in different CF- and ICF-channels as a function of mode of reactions.
The spin-distributions of $\alpha x n$-channels populated via CF and ICF in $^{12}$C,$^{16}$O+$^{169}$Tm systems are plotted in Fig.4(a-b). The nomenclature used in this figure indicate the involved reaction dynamics, i.e., ‘B’ and ‘F’ respectively indicate CF-channel: identified from backward(B)-$\alpha$-gated spectra, and ICF-channel: identified from forward(F)-$\alpha$-gated spectra. As shown in Fig.4(a), there is a striking difference in the spin-distributions of different channels which indicate the involvement of entirely different mode of reactions in the production of these residues. The intensity of $\alpha x n$(singles)/$\alpha x n-B$-channels (CF residues) falls off rather quickly with observed spin ($J_{obs}$), indicating strong feeding and/or broad spin population during the de-excitation of CN. However, for $\alpha x n-F$-channels (ICF residues), the intensity appears to be almost constant up to a certain value of $J_{obs}$, and then decreases towards band head. This indicates the absence of feeding to the lowest members of the ‘yrast’ band and/or the population of low spin states are strongly hindered in ICF-channels.

In order to understand the multitude of mean $\ell$-values, and to examine the possibility to populate high spin states via ICF, the value of $\ell$ involved in CF- and ICF-channels have been deduced from the analysis of experimental spin-distributions. The $\ell$-values involved in various modes of reactions are plotted in Fig.4(b). As can be seen from this figure, the value of $\langle \ell \rangle$ involved in the production of CF-$\alpha x n$/pxn-$B$/pxn-$B$, and ICF-$\alpha x n-F$, and ICF-$2\alpha x n-F$ channels are found to be $\approx 7.5 \ h$, $\approx 10 \ h$ and $\approx 13.5 \ h$, respectively, at projectile energy $\approx 5.6 \ AMeV$ for $^{12}$C+$^{169}$Tm system. However, at projectile energy $\approx 6.5 \ AMeV$, the value of $\langle \ell \rangle$ for CF-$\alpha x n$/pxn-$B$/pxn-$B$, and ICF-$\alpha x n-F$, and ICF-$2\alpha x n-F$ channels are found to be $\approx 10h$, $\approx 14h$ and $\approx 17h$, respectively. The enhancement in the value of $\langle \ell \rangle$ in case of direct-$\alpha$-emitting channels (ICF residues) indicates their origin from high $\ell$-values as compared to CF-channels. A very useful correlation between the value of $\langle \ell \rangle$ and the successively opened ICF channels can be obtained from the data presented in Fig.4(b). The value of $\langle \ell \rangle$ associated with ICF in contrast with CF can be represented as [4]:

(a) for $^{12}$C($E_{lab}$$\approx$5.6 AMeV)+$^{169}$Tm system,

$\ell_{ICF-\alpha x n}$$\approx$1.33$\ell_{CF-\alpha x n}$/pxn/$\alpha x n$,

$\ell_{ICF-2\alpha x n}$$\approx$1.35$\ell_{ICF-\alpha x n}$ and $\ell_{ICF-\alpha x n}$ $\approx$1.8$\ell_{CF-\alpha x n}$/pxn/$\alpha x n$.

(b) for $^{12}$C($E_{lab}$$\approx$6.5 AMeV)+$^{169}$Tm system,

$\ell_{ICF-\alpha x n}$$\approx$1.4$\ell_{CF-\alpha x n}$/pxn/$\alpha x n$,

$\ell_{ICF-2\alpha x n}$$\approx$1.2$\ell_{ICF-\alpha x n}$ and $\ell_{ICF-\alpha x n}$ $\approx$1.7$\ell_{CF-\alpha x n}$/pxn/$\alpha x n$.

It is interesting to note that the values of $\langle \ell \rangle$ involved in ICF-$\alpha x n/2\alpha x n$-channels are found to be $\approx$ 30 to 70 % higher as compared to the CF-$\alpha x n$/pxn/$\alpha x n$-channels. This clearly suggests the involvement of high $\ell$-values in the production of ICF-products at a constant projectile energy, essentially due to peripheral interactions, where a significant amount of orbital angular momentum between projectile and target nucleus transformed into high spin states of final reaction products. It can also be observed from Fig.4(b), the involved $\ell$-values in different reaction channels are found to increase linearly with the projectile energy. The CF is not able to approach the value of $\langle \ell \rangle$ even at $\approx$ 6.5 AMeV which has been populated via ICF for the same residue at low projectile energy. The above striking features strongly support the possibility to populate high spin states via ICF in final reaction products even at low incident energy. The partial waves of lower $\ell$-values do not contribute to the ICF significantly. Therefore, it may not be out of order to state that ICF events occur in the peripheral interactions, probably at finite values of impact parameters.
4. Summary and conclusions

In summary, the ICF fraction has been measured from the analysis of differential EFS within the framework of statistical model code PACE4. The value of $F_{ICF}$ has been presented as a function of projectile energy ($E_{lab}$), mass-asymmetry ($\mu_A$), $Q_\alpha$, and input angular momenta ($\ell$). Existence of ICF at energy as low as $\approx 7.5\%$ above the barrier is conclusively demonstrated. It has been found that the value of $F_{ICF}$ increases from $\approx 7\%$ to $\approx 18\%$ with in the studied energy range (i.e., 1.02$E_b$ to 1.64$E_b$). The onset of ICF at relatively lower value of $v_{rel}$ i.e., $\approx 0.027$ ($F_{ICF} \approx 7\%$) in $^{12}$C+$^{169}$Tm system, and at $\approx 0.014$ ($F_{ICF} \approx 10\%$) in $^{16}$O+$^{169}$Tm system has been presented. In both the cases, the observed value of $F_{ICF}$ is significant at well below the proposed onset value of $v_{rel}$ (i.e., 6 % of c).

A comparison three projectile-target combinations (i.e., $^{12}$C+$^{169}$Tm and $^{16}$O+$^{169}$Tm) displays higher ICF probability for $^{16}$O+$^{169}$Tm system. This indicates strong projectile dependence on $F_{ICF}$. The existence of ICF at well below the proposed onset value of $v_{rel}$ (i.e., 6 % of c) conclusively supplements Morgenstern's mass-asymmetry systematics. The effect of $Q_\alpha$-value on ICF fraction has been observed for strongly bound projectiles. The fraction of ICF has been found to decrease for large negative $Q_\alpha$-value projectiles. If confirmed for other projectile-target combinations, this may provide an important input to understand the complex ICF dynamics at low incident energies. More experiments are planned to cover this aspect.

The spin-distribution(s) associated with ICF are found to be originated from the narrow spin population, localized near and/or above to the critical angular momentum ($\ell_{crit}$) for CF, where a given direct-\alpha-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 $\ell_{crit}$ for normal fusion (CF). It has been found that the direct $\alpha$-multiplicity increases with the value of $<\ell>$ at a particular projectile energy. For an example, at $\approx 5.6$ AMeV the value of $<\ell>$ for CF-xn/pxn-B/$\alpha$xn-B, and ICF-$\alpha$xn-F, and ICF-2$\alpha$xn-F channels are found to be $\approx 7.5\ h$, $\approx 10\ h$ and $\approx 13.5\ h$, respectively. It can be safely inferred that the high $\ell$-values associated with peripheral interactions contribute to open up direct-$\alpha$-channels. The value of $<\ell>$ associated with $2\alpha$-emitting channel likely to be originated from higher impact parameters as that associated with the production of single $\alpha$-channel.

Acknowledgments

The authors thank Prof. Amit Roy, Director of IUAC for extending experimental facilities to perform these experiments. One of the authors (P.P.S.) acknowledge the financial support from HIC for FAIR during his stay at GSI Helmholtz Center for Heavy-Ion Research GmbH, Germany, and Prof. Hans-Juergen Wollersheim and Prof. Juergen Gerl for their support and motivation during the analysis of this work. Authors R. P., B. P. S. & D. P. S. thank to DST and UGC for financial support.

References

[1] Kamal Kumar et al., Phys. Rev. C 88, 064613 (2013)
[2] D. J. Hinde and M. Dasgupta, Phys. Rev. C 81, 064611 (2010), and the references therein.
[3] Alexis Diaz-Torres, J. Phys. G: Nucl. Part. Phys. 37, 075109 (2010), and the references therein.
[4] Pushpendra P. Singh et al., Phys. Lett. B671, 20 (2009); Phys. Rev. C80, 064603 (2009), Phys. Rev. C78, 017602 (2008); and the references therein.
[5] L. R. Gasques et al., Phys. Rev. C79, 034605 (2009); Phys. Rev. C74, 064615 (2006).
[6] Devendra P. Singh et al., Phys. Rev. C81, 054607 (2010).
[7] P. R. S. Gomes et al., Phys. Lett. B601, 20 (2004); Phys. Rev. C73, 064606 (2006); Phys. Rev. Lett. B53, 1630 (1984).
[8] A. Diaz-Torres et al., Phys. Rev. Lett. 98, 152701 (2007).
[9] E. Z. Buthelezi et al., Nucl. Phys. A734, 553 (2004).
[10] Umamti Gupta et al., Phys. Rev. C80, 024613 (2009).
[11] Pushpendra P. Singh et al., Phys. Rev. C77, 014607 (2008), Euro. Phys. J. A 34, 29 (2007).
[12] Unnati Gupta et al., Nucl. Phys. A811, 77 (2008), and the references therein.
[13] Abhishek Yadav et al., Phys. Rev. C 85, 064617 (2012), Phys. Rev. C 86, 014603 (2012), and the references therein.
[14] Pushpendra P. Singh et al., Euro. Phys. Jour. WoC 21, 10009 (2012); Euro. Phys. Jour. WoC 17, 03007 (2011), and the references therein.
[15] J. Wilczynski et al., Phys. Rev. Lett. 45, 606 (1980); Nucl. Phys. A373, 109 (1982).
[16] K. Siwek-Wilczynska et al., Phys. Rev. Lett. 42, 1599 (1979).
[17] H. Morgenstern et al., Z. Phys. A313, 39 (1983); Phys. Rev. Lett. 52, 1104 (1984); Z. Phys. A324, 443 (1986).
[18] T. Inamura, et al., Phys. Rev. C 32, 1539 (1985).
[19] I. Tserruya et al., Phys. Rev. Lett. 60, 14 (1988).