Reconciliation of mass-asymmetry systematics for incomplete fusion

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Abstract. The onset and strength of incomplete fusion (ICF) has been studied in the framework of Morgenstern’s mass-asymmetry systematics. The fraction of ICF has been deduced in $^{12}\text{C}+^{169}\text{Tm}$ system at energies ranging from 1.02$V_b$ to 1.64$V_b$ ($V_b = 54.94$ MeV from the analysis of excitation functions (EFs). It has been found that the ICF starts influencing complete fusion at noticeably lower $\beta$-values (i.e., 0.025 or 2.5 % of $c$) than that proposed by Morgenstern (i.e., $\approx 6\%$ of $c$). The fraction of ICF increases with entrance channel mass-asymmetry for individual projectiles, termed as projectile dependent mass-asymmetry (ProMass-) systematics. The proposed ProMass - systematics has withstood all tests that have been done for fairly large number of systems to verify its validness.

1. Introduction
Existence of incomplete fusion (ICF) at low incident energies, where the interactions between two heavy-ions(HIs) are mainly dominated by complete fusion(CF), has gained resurgent interest [1, 2, 3, 4, 5, 6]. Recently, a substantial ICF fraction has been observed at energies as low as $\approx$3-7 MeV/nucleon [7, 8].

Since the very first observation of ICF [9, 10], a variety of studies have been performed to understand the onset and dynamics of ICF [11]. Despite the existing studies (see refs.[2, 7] for detail), the dynamics of ICF at these energies is still not fairly understood, thus continues to be an active area of investigations. The main issues of previous studies were to explore the effects of; (i) projectile energy, (ii) mass-asymmetry ($\mu_A = A_T/A_T+P$), and (iii) input angular momenta on the onset and strength of ICF. Some of the important conclusions drawn from the previous studies are; (i) at high $\ell$-values ($\ell \geq \ell_{crit}$), projectile breaks up into constituents to provide sustainable input angular momenta, and fuses partly with target nucleus [2, 12, 13], (ii) the partially fused composite (PFC)-system forms with less mass/charge and recoil velocity as that of completely fused composite (CFC)-system [6, 14, 15, 16], (iii) the fraction of ICF has been found to be large for more mass-asymmetric systems [17]. However, some of the experimental results contradict previous findings. For example, according to Morgenstern’s systematics [17], the fraction of ICF is expected to be large for more mass-asymmetric systems at a constant
value of \( v_{\text{rel}} \) (i.e., \( \sqrt{2(E_{\text{cm}} - V_b)/\mu/c} \)). In recent reports [7, 8], the variation of ICF fraction with \( \mu_A \) do not found to obey Morgenstern’s systematics. While, the data obtained for individual projectiles (\(^{12}\text{C}\) and \(^{16}\text{O}\)) have been fairly explained by the given systematics. This observation may be considered as a supplement to the systematics but rather poorly known, therefore, need to be supported by further measurements. To confirm the findings of ref.[7, 8], and to have better insights into the entrance channel effect on the onset and strength of ICF, the fraction of ICF has been deduced in \(^{12}\text{C}+^{169}\text{Tm}\) system at energies ranging from 1.02\(V_b\) to 1.64\(V_b\) (\(V_b = 54.94\) MeV). Findings of present measurement are compared with the previously reported \(^{16}\text{O}\) results [7] to display projectile effect on ICF fraction. A comparison of results from nearby systems, \(^{12}\text{C}+^{128}\text{Te}, ^{165}\text{Ho}, ^{169}\text{Tm}\) and \(^{16}\text{O}+^{103}\text{Rh}, ^{159}\text{Th}, ^{169}\text{Tm}\) [7, 8, 18, ?], is also presented to describe mass-asymmetry (and/or projectile) dependence on the onset and strength of ICF.

![Figure 1](image)

**Figure 1.** (a) Decay \( \gamma \)-lines of different residues are marked in a spectra obtained at \( \approx 89.3 \) MeV, (b) Decay curve of \(^{177}\text{Re}\) \((t_{1/2} = 14\text{ min})\) obtained by following 197 keV \( \gamma \)-line.

2. **Experimental details and data analysis**

Experiments have been performed at IUAC New Delhi using similar experimental methodology and setup as has been used in refs.[7, 8]. However, a brief account of experimental conditions is given here. \(^{169}\text{Tm}\) (abundance = 100\%) Targets of thickness \( t_m \approx 1\text{ mg-cm}^{-2} \) were prepared by rolling technique and the uniformity of each target was verified by \( \alpha \)-transmission method. The error in thickness was estimated to be \( \approx 1\% \). In ref.[7, 8], energy degradation technique has been employed to cover a wide energy range in single run, and corrections were made for energy spread and beam intensity variations during the data analysis. In this work, the energy spread and beam intensity variations have been avoided by adopting single target irradiation methodology for each projectile energy. Irradiations were carried out using \(^{12}\text{C}\)-beam \((E_{\text{beam}} = \approx 54-90\) MeV, beam current \( \approx 20-30\) nA). In-situ measurements of \( \gamma \)-activities were performed off-line using two pre-calibrated HPGe detectors to detect the residues of short half-lives \((t_{1/2} \approx 5-10\) minutes). The uncertainty in efficiency of detectors is estimated to be \( \approx 2\% \). Relevant portion of a \( \gamma \)-ray spectra obtained at \( \approx 89\) MeV is shown in Fig.1(a), and a decay curve for \(^{177}\text{Re}\) residue in Fig.1(b). Reaction products have been identified by their characteristic \( \gamma \)-lines.
and decay-curve analysis. The most intense $\gamma$-lines have been used for decay-curve analysis and for the production cross-section ($\sigma_{ER}$) measurement [8]. The overall error in $\sigma_{ER}$ is estimated to be $\approx 13\%$.

Figure 2. (a) EFs of individual ICF channels in $^{12}$C+$^{169}$Tm system, (b) comparison of $\Sigma \sigma_{ICF}$ with $\Sigma \sigma_{CF}$ and $\sigma_{TF}$, (c) the ICF strength function for different systems (see text for description), and (d) the values of $F_{ICF}$ as a function of $\mu_A$.

3. Results and interpretations
The ICF strength function has been deduced for $^{12}$C,$^{16}$O+$^{169}$Tm systems from the analysis of experimental EFs in the framework of statistical model code PACE4 [6, 7]. Detailed discussion on data reduction procedure can be found elsewhere [6, 7]. Experimentally measured and systematically deduced EFs for individual ICF channels are plotted in Fig.2(a), and the sum of all ICF-channels ($\Sigma \sigma_{ICF}$) is plotted with the sum of all CF-channels ($\Sigma \sigma_{CF}$) and total fusion ($\sigma_{TF}$) in Fig.2(b). The separation between $\Sigma \sigma_{CF}$ and $\sigma_{TF}$ with $E_{lab}$ indicates increasing ICF contribution with energy. In order to better understand the energy dependence, the percentage fraction of ICF ($F_{ICF}$) is plotted with $E_{lab}$ in Fig.2(c), termed as ICF strength function. The ICF strength function defines empirical probability of ICF at different projectile energies. As shown in Fig.2(c), the value of $F_{ICF}$ is found to be $\approx 7\%$ at $\approx 59$ MeV, i.e., $1.075V_{b}$ (7.5 $\%$ above...
the barrier), and increases smoothly up to \( \approx 18\% \) at highest measured energy i.e., 1.64 \( \text{Vb} \) for \( ^{12}\text{C}+^{169}\text{Tm} \) system.

According Morgenstern’s systematic [17], ICF contributes significantly above \( v_{\text{rel}} = \beta = 0.06 \) (6 \% of c), and the fraction of ICF should increase with entrance channel mass-asymmetry (\( \mu_A \)). As can be seen in Fig.2(c), the values of \( \beta \) are in the range from \( \approx 0.027 \) (2.7 \% of c) to \( \approx 0.084 \) (8.4 \% of c) for \( ^{12}\text{C}-\text{beam} \), and from \( \approx 0.014 \) (1.4 \% of c) to \( \approx 0.053 \) (5.3 \% of c) for \( ^{16}\text{O}-\text{beam} \).

At given value of \( \beta \), no significant ICF contribution is expected. But, the results presented here suggest the onset of ICF at relatively lower value of \( \beta \) i.e., \( \approx 0.027 \) (F \( \text{ICF} \approx 7\% \)) in \( ^{12}\text{C}+^{169}\text{Tm} \) system, and at \( \approx 0.014 \) (F \( \text{ICF} \approx 10\% \)) in \( ^{16}\text{O}+^{169}\text{Tm} \) system. In both cases, the observed value of F \( \text{ICF} \) is significant even at well below the proposed onset value of \( \beta \) (i.e., 6\% of c).

Further, the value of F \( \text{ICF} \) for \( ^{12}\text{C} \) is lower than \( ^{16}\text{O} \)-projectile. The difference in F \( \text{ICF} \) for two systems \( (^{12}\text{C},^{16}\text{O}+^{169}\text{Tm}) \) indicates the dependence of F \( \text{ICF} \) on projectile charge and/or on \( \mu_A \). In order to refine this effect, the values of F \( \text{ICF} \) for nearby systems \( (^{12}\text{C}+^{126}\text{Te},^{165}\text{Ho},^{169}\text{Tm} \) and \( ^{16}\text{O}+^{169}\text{Rh},^{159}\text{Nb},^{169}\text{Tm}) \) are plotted as a function of \( \mu_A \) in Fig.2(d) at a constant value of \( \beta = 0.053 \). As shown in this figure, the Morgenstern’s systematics does not explain the variation of F \( \text{ICF} \) with \( \mu_A \). However, the value of F \( \text{ICF} \) increases with \( \mu_A \) for individual projectiles \( (^{16}\text{O},^{12}\text{C}, \) and \( ^{14}\text{N}) \). It is interesting to note that the \( ^{12}\text{C}+^{169}\text{Tm} \) system is a more mass-asymmetric \( (\mu_A = 0.9337) \) than \( ^{16}\text{O}+^{169}\text{Tm} \) system \( (\mu_A = 0.9135) \), but the value of F \( \text{ICF} \) is 18\% higher than that observed for \( ^{12}\text{C}+^{169}\text{Tm} \) system. Present observations suggest the inclusion of projectile effect along with the mass-asymmetry of interacting partners to explain low energy ICF and lead to the reconciliation of Morgenstern’s systematics.

4. Summary and conclusions

This paper briefly summarizes the findings of recent experiments performed to study ICF at energies \( \approx 4-7 \text{MeV/nucleon} \) in \( ^{12}\text{C},^{16}\text{O}+^{169}\text{Tm} \) systems. It has been found that ICF significantly contributes to total reaction cross-section even at slightly above barrier energies. The percentage fraction of ICF increases with projectile energy and \( \mu_A \) for individual projectiles. This suggests the inclusion of projectile type along with the mass asymmetry to explain low energy ICF data and formulate a ‘projectile dependent mass-asymmetry (ProMass) systematics’. In order to gain confidence in the proposed systematics a series of similar experiments are in order.

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