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# Incomplete fusion at energies ≈ 4-7 MeV/nucleon: recent results

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**Abstract.** Aiming to investigate the presence of incomplete fusion at low projectile energies, experiments have been carried out using light heavy-ion (A ≤ 16) beams at ≈ 4-7 MeV/nucleon. Excitation functions, forward recoil ranges, and spin-distributions of heavy reaction products have been measured. In order to have an insight into the influence of incomplete fusion on complete fusion, percentage fraction of incomplete fusion has been deduced from the experimentally measured excitation functions. However, the proof of fractional linear-momentum transfer in case of incomplete fusion has been obtained from the measurement of forward recoil ranges of heavy reaction products. A piece of information on driving angular momenta involved in the production of xn/pxn/$\alpha$xn/2$\alpha$xn-channels has been obtained from the analysis of experimentally measured spin-distributions. Results presented in this paper strongly suggest that incomplete fusion is a process of greater importance at energies ≈ 4-7 MeV/nucleon and can selectively populate high spin states in final reaction products.

## 1 Introduction

In recent years, incomplete fusion (ICF) of light heavy-ions (A ≤ 16) has been intensively investigated at energies ≈ 4-7 MeV/nucleon [1–5], where only complete fusion (CF) is supposed to be dominant. The CF is said to occur when entire projectile fuses with target nucleus. While, only a part of projectile fuses with target nucleus in case of ICF and unfused fragment continues to move in forward cone with almost projectile velocity [6,7]. The important characteristics of ICF are given elsewhere [2,3]. In order to understand ICF dynamics, several theoretical models (see in ref.[2,3,5]) have been proposed. The existing models qualitatively explain the experimental data particularly at E/A ≥ 10.5 MeV, But are not consistent at energies ≈ 4-7/nucleon. As such, the study of ICF at given energies is still an active area of investigations. The main motivation of ICF studies is to explore the effect of various entrance channel parameters, such as; (*i*) projectile energy, (*ii*) mass-asymmetry of interacting partners, and (*iii*) driving angular-momenta. In addition to that, some outstanding issues related ICF are, (*i*) to examine the possibility to produce high spin states via ICF, and (*ii*) the localization of $\ell$-values. In view of the above issues, experiments have been performed to measure excitation functions (EFs), forward recoil ranges (FRRs), and spin-distributions (SDs) of heavy reaction products [2,3,5]. In this paper, a summary of exciting recent results on ICF is presented. This paper is organized as follows; an approach to deduce percentage ICF fraction ($F_{ICF}$) from the analysis of EFs is given in section 2.1. While, the validation of the approach to deduce percentage $F_{ICF}$ is presented in section 2.2. Section 2.3 deals with the measurement of SDs to examine the possibility to populate high spin states in final reaction products via ICF, and to understand the localization of $\ell$-values in different reaction products. The summary and conclusions of the present work are given in the last section of this paper.

## 2 Measurements and Observations

In order to understand low energy ICF, experiments have been carried out at the Inter-university Accelerator Center (IUAC), New Delhi, India. For the measurement of EF's and FRRs, activation technique followed by off-line $\gamma$-spectroscopy has been used. While, particle-$\gamma$-coincidence technique has been employed for the measurement of SDs. Some of the interesting recent results on ICF are given in the following sub-sections. However, the details of these measurements can be found in refs.[2–5].

### 2.1 Influence of ICF on CF

As has already been mentioned in earlier section, percentage $F_{ICF}$ has been deduced for $^{16}O+^{113}Rh,^{159}Tb,^{169}Tm$ systems [2,3] at energies 4-7 MeV/nucleon to understand the influence of ICF on CF. It may be pointed out that, it is not possible to directly obtain the relative contributions of CF and ICF from the measurement of EFs. Therefore,

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an indirect method (see in refs.[2,3]) has been used to deduce ICF contribution. The experimentally measured EFs have been analyzed using theoretical model code PACE [8]. In this code, level density parameter a( = A/K MeV$^{-1}$) is an important parameter. The value of K may be varied to calibrate the code as per experimental conditions. We tested different values of K (K = 8-11), where a value of K = 8, i.e., a = A/8 MeV$^{-1}$ is found to reproduce the EFs of non-$\alpha$-emitting channels. However, in most of the $\alpha$-emitting channels, a significant enhancement in the cross-sections over the theoretical predictions has been observed. Assuming this enhancement as a contribution of ICF (since PACE4 don't predict ICF), the percentage $F_{ICF}$ has been deduced as a function of projectile energy and mass-asymmetry of interacting partners (refer to Fig.1). As indicated in Fig.1a, the value of $F_{ICF}$ found to be increases with projectile energy for the given projectile-target combinations, in general. Particularly, the value of $F_{ICF}$ is found to be ≈ 5.5 %, ≈ 20 % and ≈ 30 % at same normalized projectile energy (i.e., $E_{beam}/V_b$ = 1.4) for $^{16}$O+$^{103}$Rh,$^{159}$Tb,$^{169}$Tm systems, respectively. This striking observation clearly reveals the sensitiveness of $F_{ICF}$ to the target mass. In order to have better insight into this aspect, the value of $F_{ICF}$ is plotted as a function of mass-asymmetry of interacting partners in Fig.1b. As can be seen from this figure, the systematics presented by Morgenstern *et al.*,[9] do not explain experimental data as a whole. The value of $F_{ICF}$ found to be increases with mass-asymmetry, individually for $^{16}$O and $^{12}$C projectiles. Therefore, it can be inferred that, not only mass-asymmetry of interacting partners but also the projectile structure effect should also be taken into account while predicting the $F_{ICF}$.

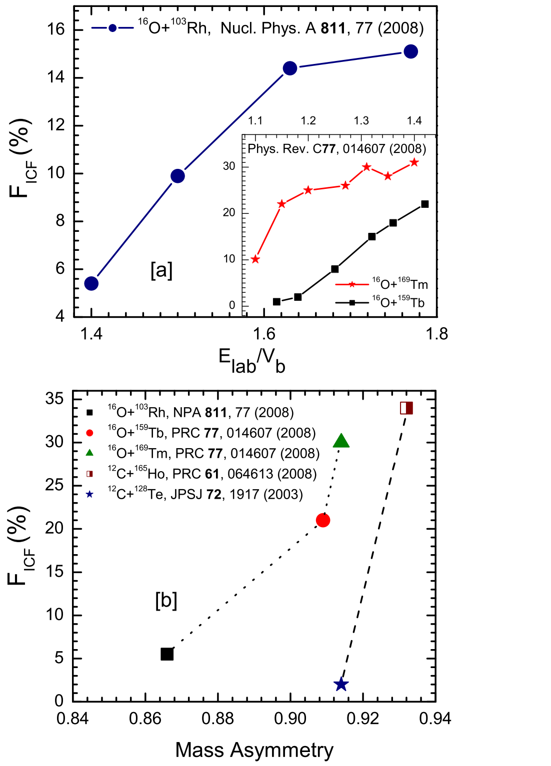


**Fig. 1.** Experimentally deduced percentage $F_{ICF}$ as a function of, (*a*) normalized projectile energy ($E_{beam}/V_b$) for $^{16}$O+$^{103}$Rh,$^{159}$Tb,$^{169}$Tm systems, (*b*) mass-asymmetry of interacting partners at a constant value of $E_{beam}/V_b$ = 1.4. Lines are drawn to guide the eyes.

### 2.2 Fractional linear momentum transfer in ICF

In order to validate data reduction procedure to deduce ICF contribution, FRRs of different reaction products have been measured. Kinematically, CF and ICF products can be disentangled on the basis of recoil velocity of the reaction products, depending upon the degree of linear momentum transfer ($\rho_{LMT}$) from projectile to the target nucleus. For ICF, $\rho_{LMT}$ may be given as;

$$\rho_{LMT} = \frac{P_{frac}}{P_{proj}} \tag{1}$$

where; $P_{frac}$ is the linear momentum of fused fraction of projectile and $P_{proj}$ is the full linear momentum of projectile. Maximum $\rho_{LMT}$ in CF is supposed to give maximum recoil velocity to the reaction products, and relatively less recoil velocity in ICF. Consequently, the radio-nuclides populated via small $\rho_{LMT}$ (ICF products) are expected to show relatively smaller absorption depth in the stopping medium as compared to the entire LMT populations (CF products). As such, most probable FRRs of heavy reaction products have been measured in $^{16}$O+$^{159}$Tb,$^{169}$Tm,$^{181}$Ta systems at different energies [2,3]. As a representative case, the profile of FRRs for $^{181}$Re($\alpha$ or 2p2n), populated in $^{16}$O+$^{169}$Tm system at ≈ 81 MeV is shown in Fig.2a. As can be seen from this figure, the profile of FRRs can be resolved into two Gaussian peaks, revealing the presence of more than one LMT components (associated with the fusion of $^{16}$O and $^{12}$C with $^{169}$Tm). The values of experimentally measured most probable FRRs ($R_P^{exp}$) are found to be ≈ 375 $\mu$g/cm$^2$ (due to $^{16}$O-fusion) and at ≈ 260 $\mu$g/cm$^2$ ($^{12}$C-fusion, and an $\alpha$ as spectator). On the basis of observed $R_P^{exp}$, it can be inferred that the residues $^{181}$Re produced via $\alpha$-emitting channel have contributions from both CF and ICF processes. This implies fractional momentum transfer in ICF. The value of $R_P^{exp}$ for different residues have also been compared with the theoretically estimated most probable FRRs by range-energy formulation in the framework of breakup fusion model[10] and are found to be in good agreement with theoretical ones (see ref.[2,3]). Further, in order to understand the energy dependence of CF and ICF components, relative strengths of CF and ICF have been deduced from the profile of FRRs. Fig.2b shows, the relative contributions of CF and ICF in the production of $^{181}$Re($\alpha$ or 2p2n) at ≈ 76, 81, 87 MeV. As shown in this figure, the CF (fusion of $^{16}$O) contribution decreases with projectile energy, while the ICF (fusion of $^{12}$C) contribution is found to increase with projectile energy. The

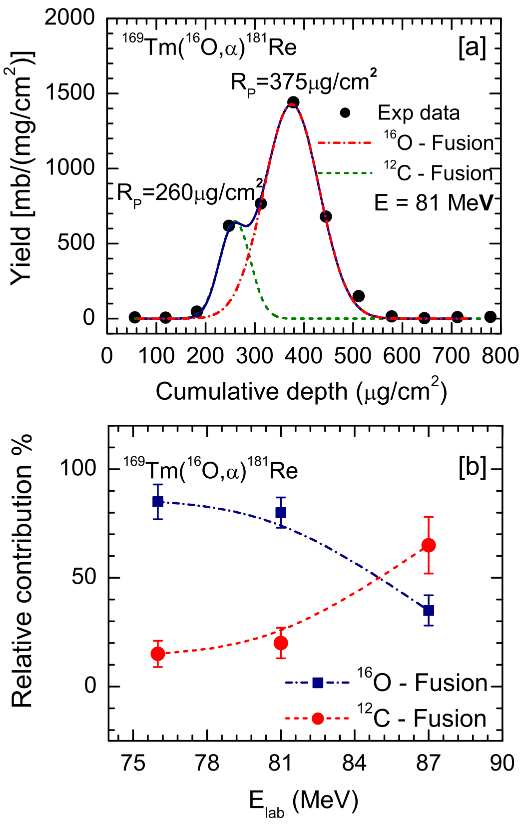


**Fig. 2.** (*a*) Experimentally measured profile of FRRs for $^{181}$Re($\alpha$/2p2n), and (*b*) Relative strengths of CF and ICF in the production of $^{181}$Re($\alpha$ or 2p2n) at projectile energies ≈ 76, 81 and 87 MeV.

observed trend reveals that the influence of ICF over CF increases with projectile energy, as expected.

### 2.3 Role of high $\ell$-values in low energy ICF

The above two sets of experiments suggest the presence of ICF at low energies but do not provide any information about the involved $\ell$-values in different reaction products and the probability to populate high spin states via ICF. As such, with a view to probe the role of high $\ell$-values in the onset of ICF at ≈ 4-7 MeV/nucleon, and to examine the possibility to produce high spin states via ICF, the SDs of xn/pxn/$\alpha$xn/2$\alpha$xn-channels have been measured in $^{12}$C,$^{16}$O+$^{169}$Tm systems at energies near and above the barrier [3,5]. In our recent letter [5], we presented a correlation between successively opened ICF channels and associated $\ell$-values. As a representative case, experimentally measured spin-distributions for $\alpha$4n-channel, identified from both Backward(B) and Forward(F)-$\alpha$-gated spectra, populated via CF and ICF in $^{12}$C,$^{16}$O+$^{169}$Tm systems are shown in Fig.3a. The nomenclature used in this figure indicate the involved reaction dynamics i.e., 'B' and 'F' respectively indicate CF and ICF. As can be noticed from Fig.3a, the intensity of $\alpha$4n-B-channels (CF) falls off rather quickly with $J_{obs}$, indicating strong feeding and/or broad spin population during the deexcitation of CN. However, for $\alpha$4n-F-channels (ICF), the intensity appears to be almost constant up to a certain value of $J_{obs}$, and then decreases towards entry side. These characteristics indicate 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 driving angular momenta ($\ell$-values), and to examine the possibility to populate high spin states via ICF, mean driving angular momenta involved in CF and ICF channels have been deduced from the spin-distributions as explained in ref.[5]. The $\ell$-values involved in various modes of reactions are plotted in Fig.3b. As indicated in this figure, the $\ell$-values involved in the production of CF-xn/pxn-B/$\alpha$xn-B, and ICF-$\alpha$xn-F, and ICF-2$\alpha$xn-F channels are found to be ≈ 7.5 $\hbar$, ≈ 10 $\hbar$ and ≈ 13.5 $\hbar$, respectively, at projectile energy ≈ 5.6 AMeV. However, at projectile energy ≈ 6.5 AMeV, the value of mean driving angular momenta for CF-xn/pxn-B/$\alpha$xn-B, and ICF-$\alpha$xn-F, and ICF-2$\alpha$xn-F channels are found to be ≈10$\hbar$, ≈14$\hbar$ and ≈17$\hbar$, respectively. The enhancement in the value of $J_{\circ}$ in case of direct-$\alpha$-emitting channels is a direct indication of their origin from high $\ell$-values as compared to fusion evaporation channels. Apart from that, the $\ell$-values associated with the production of $^{173}$Ta via CF at ≈ 6.5 AMeV (i.e., ≈ 9.5 $\hbar$) is achieved via ICF even at lower projectile energy ≈ 5.6 AMeV (i.e., ≈ 10.5 $\hbar$). Similar characteristics have been observed in case of other reaction channels populated via both CF and ICF. As such, an approximate but quite useful correlation emerged from these measurements about the possibilities to populate high spin states, and can be represented as;

(*i*) $^{173}$Ta($\alpha$4n), at ≈ 5.6 AMeV;

$\ell_{(ICF-\alpha 4n-F)} \approx 1.33\ell_{(CF-\alpha 4n-B)}$,

(*ii*) $^{173}$Ta($\alpha$4n), at ≈ 6.5 AMeV;

$\ell_{(ICF-\alpha 4n-F)} \approx 1.4\ell_{(CF-\alpha 4n-B)}$, and

(*iii*) $^{173}$Ta($\alpha$4n);

$\ell_{(ICF-\alpha 4n)}(5.6\ \text{AMeV}) \approx 1.1\ell_{(CF-\alpha 4n)}(6.5\ \text{AMeV})$

As mentioned above, ICF can populate $^{173}$Ta($\alpha$4n) at ≈ 33 % more angular momentum as compared to that populated via CF at ≈ 5.6 AMeV, and ≈ 40 % more at ≈ 6.5 AMeV. Further, it is also clear from the (*iii*)-correlation that, the CF is not able to approach the value of populated angular momenta even at ≈ 6.5 AMeV which has been populated via ICF for the same residue at relatively low projectile energy, i.e., ≈ 5.6 AMeV. The above striking features strongly support the possibility to populate high spin states via ICF in final reaction products even at low projectile energy.

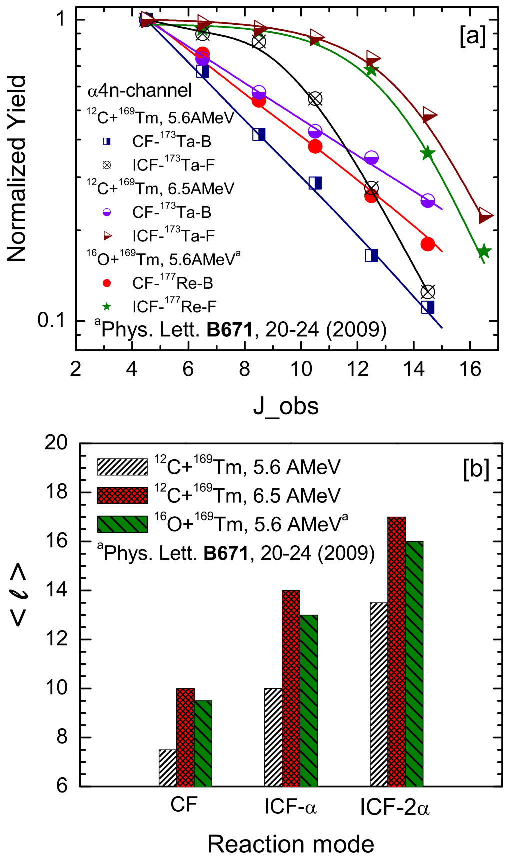


**Fig. 3.** (*a*) Experimentally measured spin-distributions for $\alpha$4n-channels populated in $^{12}$C,$^{16}$O+$^{169}$Tm system. Reaction products have been labeled by self-explanatory notations and emission cascades. The lines and curves through the data points are the result of best fit procedure explained in ref.[5], and (*b*) The $\ell$-values involved in various CF and ICF channels as a function of modes of reaction.

## 3 Summary and conclusions

In this paper, some recent results on ICF have been presented at energies $\approx$ 4-7 AMeV. It has been observed that, ICF is a process of greater importance at these energies. The probability of ICF is found to increase with projectile energy and mass-asymmetry of interacting partners for different projectiles. In order to confirm the findings of EFs measurements, the profile of FRRs have been measured for the same projectile-target combinations at different energies. From the analysis of the profile of FRRs, it has been observed that the $\alpha$-emitting channels have significant contribution from both CF and ICF. As an example, in case of $^{181}$Re, two LMT components associated with $^{16}$O and/or $^{12}$C-fusion have been observed. This indicates the population of this residue both via CF and ICF processes, and supports the breakup fusion description of ICF reaction [10]. The $R_P^{exp}$ are found to consistent with the theoretical predictions, within the experimental errors. The spin-distributions of ICF-$\alpha$xn/2$\alpha$xn-channels (identified from forward-$\alpha$-gated spectra) are found be distinctly different than that observed for CF-xn/pxn/$\alpha$xn-channels, which indicates entirely different de-excitation patterns for CF and ICF from entry states to the 'yrast' line. The pattern of SDs (associated with CF) reflect strong feeding and population of broad spin range towards the band head. However, the SDs associated with ICF expected to be arrised from the narrow spin population, localized near and/or above to the critical angular momentum for CF, where a given projectile-like fragment is emitted to release the excess driving angular momenta. This indicates the competition from successively opened ICF channels for each $\ell$-value above $\ell_{crit}$ for normal fusion (CF) at respective projectile energies. In addition, the population of low spin states is observed to be hindered and/or less fed in case of ICF, which reveals that the ICF predominantly occurs due to the influence of centrifugal potential in peripheral interactions, where driving angular momentum limit do not allow CF. Further, it has also been shown that the direct $\alpha$-multiplicity increases in forward cone with the mean value of driving angular momenta at a particular projectile energy. Further, from the comparison of $\ell$-values involved in the production of direct-$\alpha$-emitting and normal-$\alpha$-emitting channels, we have obtained direct evidence that ICF can populate high spin states in final reaction products which are not possible to achieve via CF at a given projectile energy.

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