Incomplete Fusion Dynamics in Reactions Induced by Alpha Cluster and Non-Alpha Cluster Projectiles at Low Energies

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Abstract. The present work is an exclusive attempt to study the incomplete fusion (ICF) dynamics in heavy-ion(HI) reactions induced by both alpha cluster and non-alpha cluster projectiles as these studies are considered to be more complex and challenging, even at energies as low as near to coulomb barrier. More experimental studies across a wide range of energies with different projectile and target combinations are needed to fully comprehend the various process in these nuclear reactions. The present study show the measurements of residual cross sections resulting from alpha cluster projectiles viz,^{12}C, ^{16}O and ^{20}Ne induced reactions and non-alpha cluster projectiles viz., ^{13}C, ^{14}N, ^{18}O and ^{19}F induced reactions on various low, medium, and high - Z targets covering the energy range of 4-7 MeV/nucleon. The off-line γ-ray spectroscopy associated with high purity HPGe detector method was used for the investigations. The data analysis was performed using statistical model codes . A noticeable contribution of incomplete fusion process was observed even at energies close to the Coulomb barrier. The incomplete fusion strength function has been analyzed in terms of projectile energy, mass asymmetry, projectile structure. A strong projectile structure effect has been observed on incomplete fusion reactions.

1 Introduction

In recent years, fusion cross sections with heavy ion nuclei have been subject of great interest for theoretical as well experimental point of view. Complete fusion (CF) and incomplete fusion (ICF) are two important reaction mechanisms at energy near and above the Coulomb barrier [1–4]. In the process of CF, the target nucleus captures the entire projectile with partial waves $\ell < \ell_{crit}$, creating a highly excited composite system known as the compound nucleus (CN). However, the ICF process involves higher values of ℓ ($\ell > \ell_{crit}$). As a result of ICF of the projectile, (i) the CN is produced with less mass/charge and excitation energy (due to fractional fusion of projectile with the target nucleus) as compared to the total mass and charge of interacting partners, however, in case of CF the CN formed with predetermined mass/charge, excitation energy and angular momenta (ii) the recoil velocity of the reaction products should be less than the complete fusion population and (iii) the angular distribution of ejectiles is expected to show maxima at forward angles. Udagawa and Tamura [5, 6] given an explanation for the formation of projectile like fragment in ICF using the distorted-wave Born approximation (DWBA). This method assumes that the projectile will split into individual a clusters, for instance, ^{16}O might split into ^{12}C + α. One part of the projectile may fuse with target nucleus, where as remaing part behaves like a spectator dominantly emitted in the forward direction. Gerschel et al.[7] published an review on ICF that suggested that the localization of the ℓ-window is dependent on the target deformation. The localization of the ℓ-window in ICF reactions was recently revealed in spin-distribution measurements as well [8].Various theoretical models have been proposed and tested to better understand the reaction dynamics of ICF systems. Wilczynski et al. [9] suggest that the ICF process appears as a result of peripheral contacts and is restricted for angular momenta (ℓ) values greater than the critical value (ℓ_{crit}) for complete fusion. In the Promptly Emitted Particles Model (PEPS) [10], the nucleons from the projectile are transported to the target nucleus and gain acceleration from the target nucleus field, resulting in an increased velocity that allows them to escape. The Exciton model [11, 12] postulates that the nucleons of the projectile encounter many collisions with the target nucleus, resulting in the creation of particle-hole excitations. These excitations then de-excite by expelling high-speed nuclear particles. It is important to mention here that above mentioned models have been successful in explaining the ICF data at energies greater than 10.5 MeV/nucleon. However, they have utterly failed to accurately replicate the experimental ICF data at lower energies, approximately 4-7 MeV/nucleon. Consequently,

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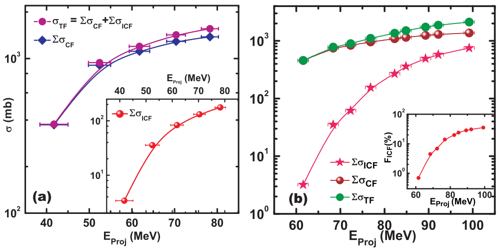

Figure 1. The total fusion cross-section $\Sigma\sigma_{TF}$ along with the sum of complete fusion and incomplete fusion cross-section ($\Sigma\sigma_{CF}$ and $\Sigma\sigma_{ICF}$) plotted as a function of incident projectile energy.[3, 14]

there is no applicable theoretical framework for low energy incomplete fusion reactions.

Studies of excitation functions of nuclear reactions are of great importance for experimental nuclear reaction databases and testing evaluated nuclear reaction data from different nuclear reaction models. The ICF reactions are quite specific due to complex nature of incomplete mass transfer and its dependence of various entrance channel parameters like type of projectile, projectile energy, mass asymmetry, and coulomb factor. To comprehend the ICF dynamics in a decisive way, our research group has measured excitation functions for a variety of nuclear reactions using alpha cluster and non-alpha cluster projectiles at low energies. The findings have been/will be appeared in our recent publications [3, 4, 14]. In this paper an attempt has been made to summarize our recent findings and develop a systematic for low energy ICF reactions.

2 Experimental Details

A series of experiments have been performed using National accelerator facility for university users at Inter University Accelerator Centre (IUAC), New Delhi, India. Targets of different spectroscopically pure materials of thickness 1.1 mg/cm^2 - 1.5 mg/cm^2 were prepared either by vacuum evaporation or rolling technique. The well established stacked foil activation technique followed by offline detection of γ- rays using HPGe detectors. The stacks of targets and aluminum catcher cum energy degrader foils were irradiated in a General Purpose Scattering Chamber (GPSC) at IUAC.The activities build-up in each target-catcher foil assembly were measured by a pre-calibrated HPGe detector coupled to a PC through a computer automated measurement and control (CAMAC) based data acquisition system CANDLE [13], developed by the IUAC. The same software [13] was also used for the analysis of γ-ray spectra. The details of the experimental arrangements, formulations, and data reduction procedures are discussed in details in our earlier publications [3, 4, 14].

3 Interpretation of results and conclusions

The first hint of ICF dynamics in HI induced reactions may be obtained by comparing the measured EFs with the theoretical predictions of statistical model based computer codes PACE-4 [15] and ALICE-91 [11, 16]. It has been observed that for low Z targets the Alice-91 works well while for targets of higher mass region PACE-4 predictions are found to be in good agreement for complete fusion channels. The enhancement of measured production cross-sections for evaporation residues populated through α- emitting channels over theoretically calculated values is mainly due to the presence of ICF along with CF dynamics in HI interactions above barrier energies[3, 4, 14]. The ICF contribution in the production of all α-emitting channels has been deduced as; $\Sigma\sigma_{ICF} = \Sigma\sigma_{expt.}$-$\Sigma\sigma_{ALICE-91/PACE-4}$. In order to see how does ICF contributes to the total fusion cross section ($\sigma_{TF} = \Sigma\sigma_{CF} + \Sigma\sigma_{ICF}$), the sum of CF cross sections of all channels $\Sigma\sigma_{CF}$ and $\Sigma\sigma_{TF}$ as a function of incident projectile energy are plotted in Fig. 1. It is evident from figure that the separation between $\Sigma\sigma_{CF}$ and σ_{TF} increases with projectile energy, which clearly shows that the contribution of ICF is more at relatively higher projectile energies. To get a proper insight into the onset and strength of ICF, the ICF strength function $F_{ICF}(\%)$ has been deduced from the measured EFs. The $F_{ICF}(\%)$ specifies the relative strength of ICF to the total fusion, and is expressed as $F_{ICF}(\%) = (\Sigma\sigma_{ICF}/\sigma_{TF})\times 100$. To examine the behaviour of ICF, Morgenstern et al.[17] introduced a new systematic, referred to as mass-asymmetry systematic, according to which, the systems that are more mass asymmetric contribute more ICF at the same relative velocity. To explore the validity of this aspect, the value of $F_{ICF}(\%)$ for the system with non-alpha cluster projectile, i.e., ^{14}N-induced reactions has been compared with those of obtained for alpha cluster projectiles, ^{12}C-induced reactions and ^{16}O-induced reactions for different targets at constant relative velocity (Vrel=0.051c) as a function of mass asymmetry (μ_A) and is shown in Fig. 2(a).The results show that the $F_{ICF}(\%)$ increases with an increase in mass-asymmetry of the systems except for ^{181}Ta, ^{169}Tm, and ^{115}In-target systems. From this figure, it

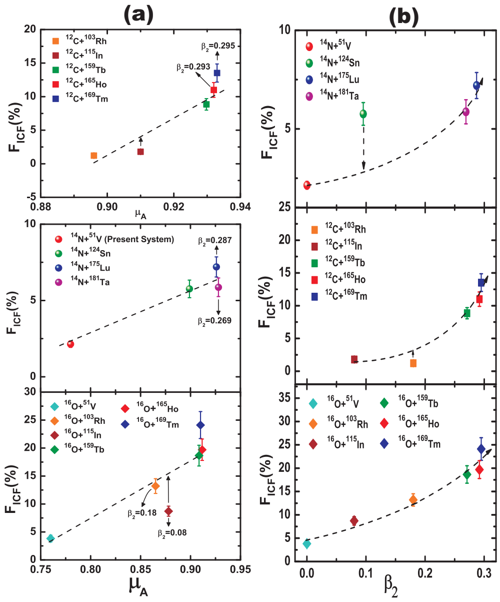

Figure 2. The deduced $F_{ICF}(\%)$ for different systems as a function of (a) mass asymmetry (μ_A) and (b) target formation parameter (β_2) at constant v_{rel} = 0.051c.[3]

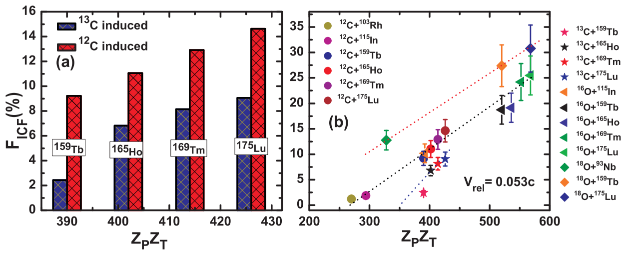

Figure 3. Comparison of deduced $F_{ICF}(\%)$ for different projectile and target systems as a function of Coulomb factor $Z_P Z_T$ at same relative velocity (v_{rel} = 0.053c). The lines drawn are just to guide the eye.

can be seen that there is a large difference in $F_{ICF}(\%)$ values for the projectile target systems having approximately same mass-asymmetry. The ICF fraction for nearly same mass asymmetric systems like ^{12}C+^{115}In (μ_A = 0.906) and ^{16}O+^{159}Tb (μ_A = 0.909) are found ≈1.79%, 18.65% and similarly for ^{12}C+^{103}Rh (μ_A = 0.896) and ^{14}N+^{124}Sn (μ_A = 0.899) are found ≈1.21%, 5.76% respectively. This shows that the ICF fraction for these systems, which have almost same mass asymmetric values, are significantly different. Which clearly shows a disparity from the systematic proposed by Morgenstern et al.[17]. The results also indicate that in addition to mass-asymmetry systematic, quadrupole deformation parameter of projectile or target may also play an important role in ICF reaction dynamics. Thus, in order to explore the influence of target deformation as well as the α-cluster structure of the projectile and its impact on the strength of ICF reactions, a comprehensive analysis is needed for various projectile target systems. To study the effect of target deformation on ICF, the deduced $F_{ICF}(\%)$ values for a number of systems have been plotted in terms of target deformation parameter (β_2) and is shown in Fig. 2(b). From this figure, it can be observed that the ICF fraction increases with an increase in the deformation parameter (β_2). Further, it is also clear from the figure that the system ^{14}N+^{124}Sn has a larger ICF fraction than that of the ^{14}N+^{51}V system. This may be due to the deformation parameter value for ^{124}Sn (β_2=0.0952) or may be due to the large value of mass-asymmetry for ^{14}N+^{124}Sn system (μ_A=0.899) as compared to the ^{14}N+^{51}V system (μ_A=0.785). Further, the inconsistency observed in $F_{ICF}(\%)$ with mass-asymmetry for ^{181}Ta, ^{169}Tm, and ^{115}In -target systems can be seen to be well-ordered in terms of the target deformation parameter (β_2). Hence, the present analysis shows that the entrance channel parameters which are related to both projectiles, as well as the target nucleus, define very well the ICF reaction dynamics.

The onset and strength of ICF in terms of the charge product of projectile-target, i.e., ($Z_P Z_T$) called Coulomb factor, where Z_P and Z_T are the atomic numbers of the projectile and target nuclei, respectively, is also explored more effectively. The variation of ICF with $Z_P Z_T$ is displayed in Fig. 3. In their study, Shuaib et al.(Phys. Rev. C 94, 014613 (2016))found that ICF probability follows a systematic linear growth with increasing $Z_P Z_T$. As can be seen from these figures, for the systems having the same $Z_P Z_T$ values, the F_{ICF} values are found to be remarkably different. However, a simple linear growth in F_{ICF} is not observed with the increase of $Z_P Z_T$, which is in contradiction to the recent findings reported by Shuaib et al.. It may also be pointed out from Fig. 3(b) that the F_{ICF} value deduced for the ^{18}O, ^{16}O, ^{12}C, and ^{13}C projectiles follows a linear trend with increasing the parameter $Z_P Z_T$. It can be noticed that α-cluster projectiles (^{16}O and ^{12}C) follow the increasing trends in ICF and lie on the same line. However, in case of non α-cluster projectiles (^{13}C and ^{18}O) also follow increasing trends in ICF but separately for each projectile. The present results indicate that the Coulomb factor ($Z_P Z_T$) also plays an important role in determining the probability of ICF up to some extent, but it is insufficient in elucidating the ICF dynamics for combinations of projectiles and targets with the same $Z_P Z_T$ values.It has been remarked from the present study that no single parameter could able to explain the ICF dynamics satisfactorily. To probe the ICF dynamics more exclusively the parameters like projectile structure, entrance channel mass-asymmetry, and Coulomb factor have to be considered wisely.

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