Dependency of low energy incomplete fusion reactions on entrance channel parameters: still a puzzle?

Abhishek Yadav[1,*], V. R. Sharma[1], Pushpendra P. Singh[2], Indu Bala[3], Prabhat Kumar[1], Anubhav Raghav[1], Md. Shuaib[1], Abhay V. Agrawal[1], D. P. Singh[1], Sunita Gupta[4], Unnati[1], M. K. Sharma[5], R. Kumar[3], S. Murlithar[3], R. P. Singh[3], B. P. Singh[1], and R. Prasad[1]

[1]*Physics Department, Aligarh Muslim University, Aligarh-202 002, India*
[2]*Physics Department, Indian Institute of Technology Ropar, Panjab-140 001, India*
[3]*NP-Group: Inter-University Accelerator Centre, New Delhi-110 067, India*
[4]*Physics Department, Agra College, Agra-282 001, India and*
[5]*Physics Department, Shri Varshney College, Aligarh-202 001, India*

During the last couple of decades, with the observation of incomplete fusion (ICF) reactions at energies in the vicinity of Coulomb barrier, considerable efforts are being employed to look for the systematics of ICF reactions at these low energies [1–6]. Complete fusion (CF) is supposed to be the sole contributor to the total fusion cross section at the energies. It is not out of place to mention that, presently, no theoretical model is available which could reproduce the low energy ICF data satisfactorily [4]. Hence, in recent years, study of low energy ICF has triggered the resurgent interest to correlate the onset of ICF with entrance channel parameters and to look for the general systematics. From literature it can be inferred that the ICF reactions have contributed significantly at energies $\approx$ 4-7 MeV/nucleon [3–5]. In brief, by definition, CF-reactions correspond to the complete amalgamation of projectile and target nuclei for input angular momentum $\ell < \ell_{crit}$, with the dominance of the nuclear force field, leading to the formation of completely fused excited composite system, which may decay via particle and/or γ-emission. For CF-reactions, the velocity distribution of residual nuclei is centered about the velocity of the center-of-mass system. However, in case of ICF-reactions, for partial waves $\ell > \ell_{crit}$ (as per sharp cut-off model), the fusion pocket disappears in the effective potential energy curve and the projectile may break-up into clusters to provide the sustainable input angular momentum. One of the fragments may fuse with the target nucleus forming the reduced excited composite system with relatively less mass, charge and excitation energy compared to previous one. While, the remnant flows in the forward direction with almost beam velocity. Some of the experimental signatures of the (ICF) reactions are *(i)* higher production yield over the statistical model code predictions, particularly for α-channels, *(ii)* fractional linear momentum transfer from projectile to the target nucleus, *(iii)* entirely distinct de-excitation pattern of ICF residues than the CF channels, *(iv)* broad angular distribution for ICF-residues the CF-events, etc.

Since the observation of ICF reactions in mid-sixties [7, 8], various models were proposed to explain these observables like; the break-up fusion model, the multistep direct reaction theory, the overlap model, SUM RULE model, etc [4]. All these models are found to fit the experimental data at projectile energies $\geq$ 10 MeV/nucleon to a large extent. At low beam energies ($\approx$3-5MeV/nucleon), the mechanism of incomplete mass transfer is not well understood. Several studies have been carried out in the recent years to understand the reactions involving incomplete mass transfer at low beam energies. The effect of various entrance channel parameters like;

*Email: abhishekyadav117@gmail.com

the beam energy, the angular momentum, the entrance channel mass asymmetry, the projectile structure in terms of alpha-Q-value and/or binding energy of the projectile have been studied and contradicting dependence of ICF-reactions on these parameters have been reported [6]. Hence, the pending question of ICF's dependence on entrance-channel parameters develop interest to understand the presence of ICF reactions at such low energies.

In order to look for the systematics for low energy ICF-reactions, series of experiments has been performed at the Inter-University Accelerator Centre (IUAC), New Delhi. In the present paper, results of excitation functions (EFs) for ^{18}O+^{159}Tb system and recoil range distribution (RRDs) for ^{12}C+^{159}Tb will be presented. The experiments have been performed using off-line γ-ray spectroscopy. In order to cover a wide energy region in a single irradiation, energy degradation technique has been used for EFs measurements. However, to trap the recoiling residues in RRDs measurements, target followed by a stack of thin Al-catcher foils have been used. The details of the experimental set-ups will be dicussed during the conference. Keeping the half-lives of interest in mind, irradiations were carried out for $\approx$ 10-12 h duration for each irradiations. The produced activities have been recorded using a high resolution, pre-calibrated HPGe detector coupled to a PC through CAMAC. A 50Hz pulser was used to determine the dead time of the spectrometer. The efficiency and energy calibration of the detector in the specified geometry was carried out using a standard ^{152}Eu source of known strength. The over all error in the measurements are estimated to be $\leq$ 15%.

The onset of ICF at slightly above barrier energies has been emphasized in the EFs measurements, however, a clear existence of ICF at low incident energies has been demonstrated by measuring more than one linear momentum transfer components in the measurement of RRDs. In order to have better understanding the fraction of incomplete fusion (F$_{ICF}$), which is a measure of relative strength of ICF to the total fusion, have been deduced from both the measurements (EFs & RRDs). The unclear or ambiguous dependences of ICF on various entrance channel parameters and several contradicting dependences of F$_{ICF}$ have been reported in recent reports [6]. Morgenstern et al. [9] correlated the ICF fraction with entrance channel mass asymmetry (mu_A). Recently, Singh et al. [3] supplemented Morgenstern's mass-asymmetry systematics by introducing the importance of projectile structure in ProMass-systematics. Apart from this, one of our papers shows the dependence of F$_{ICF}$ on the target mass or Z$_P$Z$_T$ of interacting partners for a wide range of projectile-target combinations [4]. Further, in one of our recent paper, the projectile structure effect on ICF has been explained by introducing the α-Q-value systematics [6]. As such, the recent experimental results on ICF will be discussed in light of existing systematics during the conference, and an attempt will be made to draw a pathway for some universal systematic for ICF at low energies.

References

[1] A. Diaz-Torres, el al., Phys. Rev. Lett. **98**, 152701 (2007).
[2] M. Dasgupta, el al., Phys. Rev. C **70**, 024606 (2004).
[3] Pushpendra P. Singh, et al., Phys. Rev. C **77**, 014607 (2008).
[4] Abhishek Yadav, et al., Phys. Rev C **85**, 034614 (2012).
[5] Abhishek Yadav, et al., Phys. Rev C **85**, 064617 (2012).
[6] Abhishek Yadav, et al., Phys. Rev C **86**, 064603 (2012).
[7] H. C. Britt and A. R. Quinton, Phys. Rev. **124**, 877 (1961).
[8] J. Galin et al., Phys. Rev. C **9**, 1018 (1974).
[9] H. M. Morgenstern et al., Phys. Rev. Lett. **52**, 1104 (1984); Z. Phys. A **313**, 39 (1983).