A comprehensive study of incomplete fusion reactions in ^{19}F + ^{169}Tm system at low energies

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A comprehensive knowledge of fusion of two heavy-ions (HI) at low energies has always been a topic of research interest [1]. Generally, at these energies, complete fusion (CF) process is a dominant candidate and contribute solely to the total fusion cross-section. However, in the last couple of decades, notable contribution of incomplete fusion (ICF) reactions along with CF has also been observed at these energies [2]. On the basis of driving input angular momentum, for all partial waves $\ell \leq \ell_{crit}$, the HI reactions predominantly take place via complete fusion (CF) process. However, in ICF reaction the fusion of entire projectile is hindered for input angular momenta $\ell \geq \ell_{crit}$, and it breaks-up into fragments. One fragment fuse with the target nucleus leading to the formation of an incompletely fused composite system (IFC). The unfused part of the projectile moves in a forward direction as spectator with beam velocity. Several theoretical models [2] have been proposed to understand the reaction dynamics of ICF, and are reliable at energies ≥ 10 MeV/nucleon. These models are not able to explain the ICF data precisely at low energies. Hence, due to the non-availability of any theoretical model at low energies, the proper understanding of ICF reactions is still not very clear. In the present work, two distinct complementary experiments viz., (i) Excitation functions (EFs) measurements and (ii) recoil range distributions (RRDs) measurements have been carried out to understand the reaction dynamics of ICF reactions at low energies. The rich experimental data set from the above two different experiments may be helpful in refining the existing theoretical models. The experiment has been carried out at the Inter University Accelerator Centre (IUAC), New Delhi, India. The full experimental details are given elsewhere [2,3]. The production cross-section of reaction residues has been analyzed within the framework of statistical model code PACE4 [4]. It has been observed that the measured EFs of *xn* and *pxn* channels are in good agreement with the PACE4 predications, which confirms the production of these residues solely via CF process [4]. However, for the residues populated via alpha-emitting channels, the experimentally measured EFs are found to be significantly higher as compared to the theoretical predications. Since, the PACE4 does not consider the ICF calculations into considerations, therefore, the enhancement in the cross-sections of alpha emitting as compared to experimental data is may be attributed due to the contribution of ICF reactions. Now in order to ascertain the above facts, the RRDs of the reaction residues of the same system ^{19}F + ^{169}Tm have also been measured and analyzed at two beam energies ≈ 96 MeV and 106 MeV respectively. In this complementary experiment, attempt has been made to extract the relative contribution of ICF and CF reactions has been disentangled on the basis of linear momentum transfer (LMT) from projectile to the target nucleus. The present technique, (i.e., the RRD) is one of the most direct and irrefutable method for separating out the CF and/or ICF events. The theoretical interpretation of momentum associated with the recoiling residues are estimated by using classical considerations and their ranges in the stopping medium are calculated via SRIM code [5]. In the present work, several recoiling residues populated via

CF and/or ICF processes have been identified and their ranges and associated momentum components have been estimated. It has been observed that the RRD data of *xn* and *pxn* channels shows single Gaussian peak indicating the presence of full LMT component involved in these channels. The deduced most probable ranges (R^{exp}) of *xn* and *pxn* channels are found to be in good agreement with that obtained from the code SRIM. Further, the deduced momentum distribution of these recoiling residues has a peak exactly corresponding to the incident beam (p^{beam}) at both the energies signifying that the residues are populated via complete momentum transfer i.e., via CF process only. On the other hand, the measured RRD of alpha-emitting channels somewhat shows different behavior. Their RRD and associated momentum distributions could be deconvoluted into more than one Gaussian peaks at different cumulative depths indicating the presence of different fusion components as a result of break-up of ^{19}F into fragments. On the basis of break-up fusion model [6], the break-up components of ^{19}F may be considered as $^{19}F \rightarrow {}^{15}N + \alpha$, & $^{19}F \rightarrow {}^{11}B + 2\alpha$, where, ^{15}N & ^{11}B may fuse with the target nucleus ^{169}Tm and α & 2α move in a forward direction as spectator. Hence, the peak at higher cumulative depth corresponds to complete LMT components (i.e., via CF process) and the peaks at lower cumulative depth corresponds to partial LMT components as a result of break-up of projectile. Moreover, the estimated momentum associated with recoiling residues are found to be in good agreement with the break-up components of the ^{19}F projectile. Further, the range integrated cross-section of different fusion components of ^{19}F projectile obtained from the RRD data has been compared with that obtained from the EFs data and shown in Fig.1. As can be observed form this figure, the ICF contribution values obtained from the analysis of present data follows the same trend as obtained from the analysis of EFs data. This self-consistency of results from both the experiments signifies the reliability of and validity of the present measurement technique for disentanglement of the ICF and CF residues. Further details will be presented.

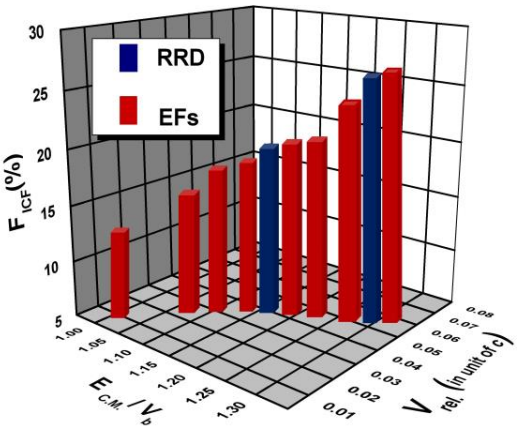

Fig.1: A comparison of ICF fraction (red vertical bars) extracted from the RRD data and ICF fraction (red vertical bars) deduced from the analysis of EFs for the residues populated via CF and/or ICF processes in ^{19}F + ^{169}Tm system [2].

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