Diffuseness in ℓ-distribution: Observation of in-complete fusion at $\ell < \ell_{crit}$

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The interest to study the in-complete fusion (ICF) reactions at energies ≈ 4-7 MeV/nucleon has aroused during the last decade due to the observation of these reactions at such low energies, where complete fusion (CF) is expected to contribute dominantly to the total fusion cross-section [1]. In case of CF, the projectiles for $\ell < \ell_{crit}$ merge with the target nucleus, with the dominance of the nuclear force field, leading to the formation of completely fused excited composite system. However, in case of ICF, for the values of $\ell > \ell_{crit}$, the projectile may break-up into clusters, one of which may fuse with the target nucleus, forming the reduced excited composite system with relatively less mass, charge and excitation energy as compared to completely fused composite system. The remnant flows in the forward direction with almost beam velocity. Due to the partial fusion of the projectile, the fractional momentum transfer takes place in the ICF processes. Each of these processes (CF & ICF) leads to the characteristic velocity distribution of the reaction residues. It may be pointed out that there are conflicting reports on the dependence of ICF on the angular momenta. The γ-multiplicity measurements done by Inamura et al. [2], and Wilczynski et al. [3], showed that ICF involves $\ell \geq \ell_{crit}$. However, study of ICF reactions on spherical targets [4] indicates the involvement of $\ell < \ell_{crit}$. This suggests that ICF competes with CF even at $\ell \leq \ell_{crit}$, contrary to the hypothesis of SUMRULE model [3] of ICF. Parker et al.[5] observed forward peaked alpha particles in reactions of ^{12}C+^{51}V at E ≈6 MeV/nucleon. Morgenstern et al. [6] measured the velocity spectra of evaporation residues (ERs) in reactions of ^{12}C, and ^{20,22}Ne beams of energies ≈ 10-25 MeV/nucleon with ^{40,44,48}Ca, and ^{58,60,62}Ni targets, where the deviation in velocity spectra from the mean velocity of complete fusion has been observed, indicating the in-complete momentum (mass) transfer from projectile to the target nucleus. In one of our recent letters [7] it has also been shown that the ICF reactions may originate during the peripheral interactions at $\ell < \ell_{crit}$.

In order to ascertain the above aspect in a consistent way, several experiments have been performed by our group at the Inter-University Accelerator Center (IUAC), New Delhi, viz; (*i*) the experiments to measure the excitation functions of radionuclides populated during the interaction of ^{12}C+^{159}Tb system at energies ≈ 1.04V$_b$ to 1.66V$_b$ [8], and (*ii*) the experiments to measure the recoil ranges of residues populated during^{12}C+^{159}Tb at several above barrier energies [9]. In these experiments the activation technique has been used. The measurement and analysis of excitation functions and the complimentary recoil range distribution measurements show a significant contribution of incomplete fusion reactions in the entire studied energy range in ^{12}C+^{159}Tb system. The cross-sections for the population of CF and/or ICF residues were also calculated using the SUMRULE model [3], which is based on the concept of localization of angluar momentum.

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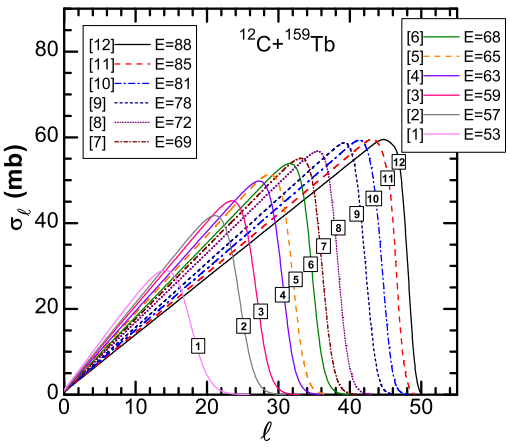

FIG. 1: The fusion ℓ-distribution for ^{12}C+^{159}Tb system at studied beam energy (E in MeV) range.

In this model, the effective temperature (T), the effective relative distance (R_c) and the diffuseness of the ℓ-distribution (Δ), are the adjustable parameters. Wilczynski et al. [3], to fit the experimetal data in the ^{14}N+^{159}Tb reactions at E_{lab} = 140 MeV, used T = 3.5 MeV, $R_c = 1.5(A_P^{1/3}+A_T^{1/3})$ and $\Delta = 1.7\hbar$. Using these parameters, the SUMRULE model calculations have also been carried out for ^{12}C+^{159}Tb system, and are found to highly underestimate the cross-sections deduced for the ICF residues [9]. As a typical example the experimentally measured cross-sections for the ($\alpha 2n$) and ($2\alpha 3n$) channels are ≈64.0±9.6 mb and 5.0±0.7 mb, however, the theoretically calculated SUMRULE values are 1.32 mb and 0.02 mb at 86 MeV beam energy.

In order to have a better understanding about the diffuseness in ℓ-distribution, the critical angular momentum ℓ_{crit} for the present system at which the pocket in the entrance channel potential vanishes has been calculated using the prescription of Wilzyanski et al., [3]. The calculations give ℓ_{crit} as 46$\hbar$. The fusion ℓ-distributions for the coumpound nucleus in ^{12}C+^{159}Tb interactions over a broad energy range ≈ 53-88 MeV have been calculated using the code CCFULL [10], and are plotted in Fig.1. The values of ℓ_{max} at studied energies, are less than the ℓ_{crit} (46$\hbar$) for fusion for this system, in general. The SUMRULE model assumes sharp cutoff ℓ values for the CF and ICF processes. The underestimation of the ICF cross-section by the SUMRULE model may be due to the assumption in the model that a major contribution to the ICF reactions comes from the collision trajectories with the angular momentum $\ell > \ell_{crit}$. It is evident from this figure that even at the highest energy studied in the present work, the population of ℓ-values are less than the ℓ_{crit} for fusion. As such, the ICF contribution is less probable at these energies as per the SUMRULE model assumptions. However, the present measurements clearly reveal the significant ICF contribution at these energies, and hence it suggests that a significant number of ℓ-waves below ℓ_{crit} may also contribute to the population of ICF residues. The details of the work will be presented.

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