A study of fusion incompleteness in heavy ion interactions at low energies

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In the present thesis work, the relative contributions of complete fusion (CF) and incomplete fusion (ICF) reactions in heavy-ion (HI) collisions were studied at energies ≈4-7 MeV per nucleon. Typically, at these energies in HI collisions, the composite system is predominantly formed via the CF process, which is expected to be the sole contributor to the total fusion (TF) cross-section [1]. However, recent observations have indicated a significant ICF contributions [2-4] at these energies sparking renewed interest. In the ICF process, for angular momentum (ℓ) $\geq \ell_{crit}$, the projectile is likely to break up into fragments. One of the fragments may fuse with the target nucleus, forming an incompletely fused composite system, while the other fragment continues to move forward with nearly the beam velocity. Several theoretical models have been proposed to understand ICF reaction dynamics, but are found to be reliable at energies ≥ 10.5 MeV/nucleon, and fail to explain ICF data at low energies. Moreover, most of the ICF studies have carried out using alpha-cluster beams such as ^{12}C, ^{16}O, and ^{20}Ne, while studies using non-alpha-cluster beams like ^{13}C, ^{14}N, ^{18}O, and ^{19}F remain limited. Therefore, extending the investigation to study ICF reactions with non-alpha-cluster beams is both interesting and may provide a better insight into the reaction dynamics.

As such, in the present work, experimental study of HI induced reactions for different systems have been performed employing different types of measurements viz., Measurements of Excitation Function (EF) for ^{14}N+^{181}Ta [5] system and measurements of Forward Recoil Range Distribution (FRRD) for ^{19}F+^{159}Tb system [6] in the energy range of ≈ 4-7 MeV/A. The experiments for these systems were performed at the Inter University Accelerator Centre (IUAC), New Delhi, India, using the 15UD Pelletron accelerator facility. The ^{14}N and ^{19}F beams were focused onto isotopically pure ^{181}Ta and ^{159}Tb, targets respectively. To cover the wide range of energy, stacked foil activation technique followed by offline γ-ray spectroscopy has been used. In the EF measurements, the reaction residues populated via CF and/or ICF processes in ^{14}N+^{181}Ta system have been identified from their characteristic γ-rays and measured half-lives.

The measured cross-section data has been analyzed within the framework of statistical model code PACE4[7]. The experimentally measured EFs of *xn* and *pxn* channels populated in above system are found to be well reproduced by the statistical model calculations and confirm the production of these channels solely via CF process. However, in the case of α-emitting channels, the experimental EFs are found to be significantly enhanced with respect to the PACE4 predictions over the entire range of energy. Since, the PACE4 code does not take the ICF into account, therefore, the large enhancement in the experimental EFs of α-emitting channels may be attributed due to the ICF processes. Further, the ICF strength function (F_{ICF}), which gives the relative contribution of ICF over CF has been deduced and its dependence on various entrance channel parameters viz., (i) incident energy (ii) Coulomb factor (Z_PZ_T) (iii) α-Q value of the projectile has been studied. Moreover, an attempt has also been made to understand the role of projectile break-up on fusion cross-section within the framework of Universal Fusion Function (UFF). An important correlation between the fusion suppression factor and break-up threshold energy of the projectiles has been observed [8].

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In the complementary measurement of FRRD, which is an irrefutable method to identify the ICF reactions, the relative contributions of CF and ICF events have been extracted on the basis of degree of linear momentum transfer from the projectile to the target nucleus. The ranges of heavy residues populated via CF and ICF processes depend on the recoil velocity, associated with the degree of linear momentum transfer from projectile to the target nucleus. In CF process, the composite system is formed via full linear momentum transfer (LMT) from projectile to the target nucleus. However, in ICF reactions, the composite system is formed as a result of break up fusion resulting in a partial LMT from projectile to the target nucleus. In the present work, the FRRD of reaction residues populated via CF and/or ICF processes in $^{19}F+^{159}Tb$ system at two distinct beam energies (83 and 94 MeV) have been measured and reported for the first time. Two different stacks, each consisting of thin ^{159}Tb target (abundance =100%) followed by a series of thin Al-catcher foils were irradiated separately. The RRD measurements provide us to determine the contributions of CF and ICF events, enabling the characterization of energy, linear momentum partitioning and the associated projectile fragmentation. A significant contribution from ICF reactions has been identified, playing a pivotal role in producing these residues. Further, it has been observed that in case of α-emitting channels connected to ICF reactions, there is a significant transfer of both partial and full momentum from the projectile to the target nucleus. The different partial linear momentum transfer components correspond to the break-up and fusion of ^{19}F projectile into ^{15}N and ^{11}B with the target nucleus. Further, the relative contribution of CF and/or ICF components have also been obtained. Also, the critical angular momentum ℓ_{crit} for the present system at which the attractive pocket in the entrance-channel potential nearly vanishes has been calculated and is found to be 79$\hbar$. The values of ℓ_{max} at two respective energies (83 and 94 MeV) in the present work are ≈ 22$\hbar$ and 40$\hbar$, respectively, which are less than the ℓ_{crit} (79$\hbar$) for fusion to occur in the present system. The observation of ICF for energies where $\ell_{max} < \ell_{crit}$ suggests that a significant number of ℓ-waves below ℓ_{crit} may contribute to ICF reactions.

Further, the validity of Bohr's theory of compound nucleus decay for $^{18}O+^{159}Tb$ and $^{12}C+^{165}Ho$ systems, forming the same compound nucleus $^{177}Ta^*$ has also been investigated [9]. In view of the above, the EFs of residues populated in $^{18}O+^{159}Tb$ and $^{12}C+^{165}Ho$ systems have been compared with the predictions of statistical model code PACE4. At lower excitation energies, the experimental cross sections for the residues $^{174}Ta(3n)$ and $^{173}Ta(4n)$ produced through two distinct entrance channels have been found to be noticeably quite dissimilar. However, at relatively higher energies, they coincide for the two entrance channels indicating the validity of independence hypothesis. The observed discrepancy in the cross sections for the two different entrance channels, at lower excitation energies for the residues of interest has been attributed to the mismatch in angular momenta. Further details will be presented.

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References

[1] P. R. S. Gomes et al., Phys. Rev. C **73,** 064606 (2006).
[2] Mohd. Shuaib, et al., Phys. Rev. C **94** 014613 (2016).
[3] Mohd. Shuaib, et al., J. Phys. G: Nucl. & Part. Phys. **44,** 105108 (2017).
[4] Mohd. Shuaib, et al., Phys. Rev. C **98,** 014605 (2018).
[5] M. Shariq Asnain et al., Phys. Rev. C **104,** 034616 (2021).
[6] M. Shariq Asnain et al., Phys. Rev. C **106,** 064607 (2022).
[7] A. Gavron; Phys. Rev. C **21**, 230 (1980).
[8] M. Shariq Asnain et al., Phys. Rev. C **105,** 014609 (2022).
[9] M. Shariq Asnain et al., Nucl. Phys. A **1041**, 122786 (2024).