Role of Projectile Break-up in Heavy-Ion Interactions at Low Energies

Mohd. Shuaib[1]*
[1]*Nuclear Physics Laboratory, Department of Physics, Aligarh Mulsim University, Aligarh-202002,INDIA*

In the present work, the relative contribution of complete fusion (CF) and incomplete fusion (ICF) reactions in the heavy-ion (HI) collisions has been studied at energies ≈ 4-7 MeV/nucleon. In the HI collisions, generally, at these energies, the composite system is predominantly formed via CF process, which is a sole contibutor to the total fusion (TF) cross-section [1]. However, in recent years, significant contribution of ICF reactions [2–4] at these energies has also been observed which has created a resurgent interest. In the ICF process, at $\ell \geq \ell_{crit}$, the projectile breaks up into fragments. One of the fragments fuses with the target nucleus, leading to the formation of an incompletely fused system, while the other one moves in the forward direction almost with the beam velocity. Several theoretical models have been developed to understand the reactions dynamics of ICF, which are found to be reliable upto some extent only at energies ≥ 10.5 MeV/nucleon, but these models could not explain the ICF data at energies ≈ 4-7 MeV/nucleon. In addition to this, most of the ICF studies have been done using the α-cluster beams like ^{12}C, ^{16}O, and ^{20}Ne. However, the studies using the non-α-cluster beams like ^{13}C, ^{14}N, ^{18}O, and ^{19}F are still limited. Therefore, it is interesting and useful to extend the investigation to study the ICF reactions using the non-α-cluster beams. In view of the above, in the present work, a comprehensive study of CF and ICF reactions at low energies has been done using the non-α-cluster beam ^{19}F on various heavy targets. The two types of complementary experiments i.e., measurement of excitation functions (EFs) and Forward Recoil Range Distribution (FRRD) have been done. The experiments were performed at the Inter University Accelerator Centre (IUAC), New Delhi using the 15UD pelletron accelerator facility. The ^{19}F beam of ≈ 3-4 pnA was focused on to isotopically pure self-suporting ^{159}Tb, ^{169}Tm, and ^{175}Lu targets. To cover the wide range of energy, stacked foil activation technique followed by off-line γ-ray spectroscopy has been used. The detailed information of experiments may be found elsewhere [2–4]. In the EF measurements, the reaction residues populated via CF and/or ICF processes in ^{19}F + ^{159}Tb, ^{19}F + ^{169}Tm, and ^{19}F + ^{175}Lu systems [2–4] in the energy range of ≈ 4-7 MeV/nucleon have been identified from their half-lives and decay curve analysis. The cross-section data has been analysed [2–4] within the framework of statistical model code PACE4 [5]. The experimentally measured EFs of xn and pxn channels populated in above systems are found to be well reproduced by the statistical model calculations and confirms the the production of these channels solely via CF process. However, in the case of α-emitting channels, the experimental EFs show significant enhancement with respect to the PACE4 predictions over the entire range of energy. It may be pertinent to mention that, 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 importance of ICF over CF has been deduced from the EFs data and its dependence on various entrance channel parameters viz., (i) incident energy, (ii) α-Q value of the projectile, (iii) mass-asymmetry of the interacting partners, (iii) Coulomb fac-

*Electronic address: `shuaibphy67@gmail.com`

tor (Z_PZ_T) etc., have been studied. Moreover, an attempt has also been made to understand the role of projectile break-up on fusion cross-section [4] within the framework of Universal Fusion Function (UFF). Significant correlation between the suppression factor and break-up threshold energy of the projectiles has been observed. In the complementary experiments for FRRD measurements, the relative contributions of CF and ICF events have been extracted on the basis of degree of linear momentum transfer (ρ_{LMT}) from the projectile to the target nucleus. The forward recoil ranges of heavy residues populated via CF and ICF processes depend on the recoil velocity, which is associated with the degree of linear momentum transfer from projectile to the target nucleus. In CF process, the composite system is formed via complete linear momentum transfer (LMT) from projectile to the target nucleus. However, in ICF process, the composite system is formed as a result of break up fusion resulting in partial linear momentum transfer (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 + ^{169}Tm system at two distinct beam energies 96 and 106 MeV have been measured and reported for the first time. The present work is in continuation of our recent investigation on ^{19}F + ^{169}Tm system, where measured EFs have been used to understand the break-up fusion processes [3]. The recoil-catcher activation technique involving off-line γ-ray spectroscopy has been employed. A series of Al-catcher foils (thickness ≈ 15-50 μg/cm^2) placed behind the thin ^{169}Tm target is used to trap the residues populated via full and partial LMT as a result of CF and ICF processes. Nine radio-nuclides viz., ^{184}Pt($4n$), ^{185}Pt($5n$), ^{184}Ir($p3n$), ^{185}Ir($p4n$), ^{183}Os(αn), ^{181}Os(α3n), ^{179}Os(α5n), ^{177}W(2α3n), and ^{175}Ta(2αp4n) have been identified from their half-lives and decay curve analysis and their RRD has been studied. In the case of xn and pxn channels, only a single Gaussian peak in the RRD has been observed that corresponds to the full LMT from projectile to the target nucleus i.e., these channels are populated via CF process. However, the RRDs of α-emitting channels are deconvoluted into more than one Gaussian peak, which strongly revealed the presence of partial LMT component associated with the ICF process. Further, the range integrated cross-sections obtanied from RRD of each residues has been deduced and compared with the values obtained from the EF data [3]. It has been observed that, the deduced ICF contribution values obtained from the analysis of RRDs agree with that obtained from the EF measurements. This clearly manifests the reliability and validity of the present measurement techniques for the disentanglement of the CF and ICF processes and indicates the self-consistent approach in the present work. Moreover, the experimentally measured ranges of reaction residues are also found to be in good agreement with those estimated by SRIM code [6]. The analysis of presently measured RRDs clearly indicates the incomplete fusion of ^{19}F projectile at energies ≈ 4-7 MeV/nucleon. As such, the non α-cluster beam also gives rise to ICF processes in nuclear interactions. Further, details will be presented.

The authors thank to the Chairperson, Department of Physics, AMU, Aligarh and to the Director, IUAC, New Delhi and to the for providing all the necessary facilities to carry out this work. BPS and MS thank to the DST project EMR/2016/002254 for financial support.

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** (2017) 105108.

[4] Mohd. Shuaib, *et al.,* Phys. Rev. C **98** 014605 (2018).

[5] A. Gavron, Phys. Rev. C **21** 230 (1980).

[6] The Stopping and Range of Ions in Matter (SRIM): [http://www.srim.org/SRIM/SRIMLEGL.htm].