Fusion incompleteness in $^{14}\text{N} + ^{169}\text{Tm}$ system: Measurement of recoil range distributions

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To understand the incomplete fusion reaction dynamics and its dependency on various entrance channel parameters, an experiment using the forward recoil range technique was performed for the $^{14}\text{N} + ^{169}\text{Tm}$ system at projectile energy $\approx 83$ MeV. The recoil-catcher activation technique followed by off-line $\gamma$-spectrometry was employed. Experimentally measured forward recoil range distributions of evaporation residues indicates the occurrence of incomplete fusion channels in addition to complete fusion. Full and partial linear momentum transfer components have been observed. The experimentally measured ranges of the evaporation residues formed due to the transfer of complete and/or partial momentum by projectile in the thin Al catchers were compared with the SRIM code. The observed incomplete fusion events can be explained on the basis of the breakup of the projectile viz. $^{14}\text{N} \rightarrow ^{8}\text{Be}$ and/or $^4\text{He}$, where $^8\text{Be}$ and/or $^4\text{He}$ fuses with $^{169}\text{Tm}$ target and transfers the partial linear momentum to the target nucleus. The present data clearly indicates that the evaporation residues were not only populated through complete fusion, but incomplete fusion also plays an important role at low projectile energy.

**Keywords:** Recoil range distribution, Complete and incomplete fusion dynamics, Heavy ion collision, Catcher stack foil activation technique, Off-line gamma spectroscopy

1 Introduction

Heavy-ion (HI) induced fusion reactions are a direct and known method to study the properties of nuclei. A complete understanding of reaction mechanism in HI-induced reaction has always been an interesting area of research. In last few years, incomplete fusion (ICF) in addition to complete fusion (CF) has emerged in HI-induced reactions above the Coulomb barrier having projectile laboratory energy ($E_{\text{lab}}$) around 4–7 MeV/nucleon$^{1,4}$. In CF reactions, complete amalgamation of projectile with the target nucleus occurs, while in the case of ICF reactions partial fusion of projectile takes place$^4$. The highly excited composite system formed via complete and/or partial fusion of the projectile de-excites by evaporating low energy nucleons followed by the decay of $\gamma$-rays. The ICF reactions were first observed by Britt and Quinton during the experimental studies of heavy ion ($^{12}\text{C}, ^{14}\text{N}, ^{16}\text{O}$) induced reactions with targets $^{197}\text{Au}$ and $^{209}\text{Bi}$ at projectile energy $\approx 7 – 10$ MeV/nucleon$^5$. Later, Inamura et al.$^6$ performed a series of experiments using particle-$\gamma$-coincidence technique. In these experiments, they observed the spin distribution of evaporation residues (ERs) populated through ICF process behave differently from those populated through CF process.

To understand ICF reaction dynamics, a variety of dynamical models have been proposed viz. Breakup fusion (BUF)$^7$, Sum rule$^8$, promptly emitted particle model (PEP)$^9$ etc. However, most of the acceptable descriptions are based on the BUF and sum rule model. In the BUF model, Udagawa and Tamura$^7$ suggested ICF as a two step process, according to which the incident projectile breaks up into its fragments in the vicinity of the target nucleus. One of the fragments may fuse with the target nucleus to form an incompletely fused composite system, and the remnant moves at forward angle with nearly projectile velocity. Contrary to this, Wilczynski et al.$^8$ in their sum rule model describe CF and ICF process on the basis of input angular momentum of the projectile ($\ell$-values). For the lower values, $\ell \leq \ell_{\text{crit}}$, the CF process is dominant, while for $\ell \geq \ell_{\text{crit}}$, the ICF process also comes in to the picture. In the case of $\ell \geq \ell_{\text{crit}}$, fusion pocket in potential energy curve is not sufficient enough to capture the entire projectile until a part of the projectile is released to provide sustainable input angular

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momentum. However, the discussed models studied ICF reactions at projectile energy \( \geq 10 \text{ MeV/nucleon} \).

For the investigation of CF and ICF dynamics, a variety of Methods are available viz. excitation functions (EFs), forward recoil range distributions (FRRDs), forward angular distributions (FADs) and spin distributions (SDs) etc. FRRD is one of the most direct and reliable method to distinguish the ICF and CF events. It is based on the linear momentum transfer from projectile to target nucleus. In CF process, linear momentum of the projectile is completely transferred to the target nuclei, while in the case of ICF process, partial linear momentum transfer takes place. The partial momentum transfer is due to the projectile break-up or peripheral collision with the target nucleus.

In the present work, the FRRD of some evaporation residues (ERs) formed in the reaction \( ^{14}\text{N} + ^{169}\text{Tm} \) at projectile energy \( \approx 83 \text{ MeV} \) have been measured. Further an effort has been made to measure the contribution of CF and ICF dynamics for individual evaporation residues from the experimental data.

2 Experimental Details

The experiment was performed using 15 UD Pelletron accelerator facility at Inter-University Accelerator Centre (IUAC), New Delhi, India, using \( ^{169}\text{Tm} \) target and \( ^{14}\text{N}^6+ \) beam at a projectile energy \( \approx 83 \text{ MeV} \). The beam current intensity was between 25nA to 30nA. The target foil (with isotopic abundance \( \sim 100\% \)) of thickness 0.5 mg/cm\(^2\) was prepared through the rolling technique at IUAC target lab. The target foil was backed with 17 Al-catcher foils of thickness ranging from 20 to 50\(\mu\text{g/cm}^2\). These foils were prepared through thermal evaporation vacuum deposition technique. The thickness of Al-catcher foils was chosen properly such that, the recoiling residues populated through CF and/or ICF process may get trapped in their respective range. The target and catcher foils assembly was mounted on the target-ladder for irradiation as depicted Fig.1

The irradiation was carried out in the General Purpose Scattering Chamber using in-vacuum transfer facility. This facility reduces the lapse time between the stop of irradiation and the beginning of the counting. The irradiation time was fixed from 8 to 10 hours in order to obtain sufficient statistics. The beam current was calculated by the total charge collected on the Faraday cup, placed just behind the target catcher foils assembly.

After irradiation target and Al-catcher foils were taken out from the chamber. A pre-calibrated High Purity Germanium detector coupled to the PC through CAMAC based CANDLE\(^{10}\) software was used for recording \( \gamma \)-ray activities induced on target and each Al-catcher foil. The populated evaporation residues were identified by their characteristic \( \gamma \)-ray energies, which were reconfirmed by the decay curve analysis.

3 Results and Discussion

In the present experiment, several ERs were identified. The measured FRRDs for the ERs \( ^{179}\text{Os}(4n), \quad ^{179}\text{Re}(p3n), \quad ^{176}\text{W}(\alpha3n) \) and \( ^{175}\text{W}(\alpha4n) \) are shown in Fig.2 (a), (b), (c) and (d). The measured yields of ERs were fitted by Gaussian distribution using the ORIGIN software\(^{11}\).

The measured FRRD of the ER \( ^{179}\text{Os} (4n) \) and \( ^{179}\text{Re} (p3n) \) show single peaks, at cumulative thickness \( \approx 347 \) and \( 362 \mu\text{g/cm}^2 \) respectively. These experimental estimated range values match satisfactorily with the theoretical values within the experimental uncertainties. The theoretical calculations are done by the SRIM-08\(^{12}\) software.

On the other hand, in Fig.2 (c) and (d), the ERs \( ^{176}\text{W} (\alpha3n) \) and \( ^{175}\text{W} (\alpha4n) \), have two distinct peaks, one of them at shorter cumulative thickness \( \approx 347 \) and \( 362 \mu\text{g/cm}^2 \) respectively. These experimental estimated range values match satisfactorily with the theoretical values within the experimental uncertainties. The theoretical calculations are done by the SRIM-08\(^{12}\) software.

![Fig. 1 – Schematic diagram of Target catcher foil arrangement used in FRRD measurement in \( ^{14}\text{N} + ^{169}\text{Tm} \) system.](image-url)
nucleus, resulting partial linear momentum from projectile to the target nucleus.

Further, the relative contributions of CF in $^{179}$Os (4n), $^{179}$Re (p3n), $^{176}$W ($\alpha$3n) and $^{175}$W ($\alpha$4n) ERs were estimated and found to be $\approx 100\%$, $100\%$, $12\%$ and $16\%$ respectively, while contribution from ICF in $^{176}$W ($\alpha$3n) and $^{175}$W ($\alpha$4n) ER have been found to be $\approx 88\%$ and $84\%$ respectively.

## 4 Summary and Conclusions

The Forward recoil range distribution measurements of $^{179}$Os(4n), $^{179}$Re(p3n), $^{176}$W ($\alpha$3n) and $^{175}$W($\alpha$4n) ERs populated via CF and/or ICF dynamic have been measured experimentally. The partial linear momentum transfer components associated with break-up of the $^{14}$N projectile into $^{8}$Be + $^4$He have been observed. The studied ERs $^{176}$W ($\alpha$3n) and $^{175}$W ($\alpha$4n) indicates the contribution not only from CF of $^{14}$N but also from ICF of $^{14}$N (fusion of fragment $^{10}$B) with target nucleus. On the basis of these FRRDs analysis, it may be concluded that the evaporation residues are not only populated via CF but ICF also plays an important role in the reaction dynamics at energies above the Coulomb barrier. The experimental data suggests break-up of $^{14}$N projectile into $\alpha + ^{10}$B at the projectile energy $\approx 83$ MeV. For complete understanding of the ICF dynamics in low energy regime (below 10 MeV/nucleon) a systematic study with different projectile target combinations is needed by considering various input entrance channel parameters which may affect the CF and ICF dynamics.

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