Dependency of incomplete fusion on target deformation

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Excitation functions for the evaporation residues \(^{161,159,158}\text{Er} (\text{xn})\), \(^{161-159}\text{Ho} (\text{pxn})\), \(^{157,155}\text{Dy} (\text{αxn})\) and \(^{155}\text{Tb} (\text{αpxn})\) populated via complete and/or incomplete fusion in system \(^{160}\text{O} + ^{148}\text{Nd}\) system at low projectile energies \(\approx 3−7\) MeV/A have been measured. In these measurements recoil catcher activation technique followed by offline γ-ray spectrometry has been used. The total measured excitation functions of the evaporation residues \(^{161,159,158}\text{Er} (\text{xn})\) and \(^{161-159}\text{Ho} (\text{pxn})\) produced through xn and pxn channels are found to be well reproduced with the total PACE-4 predictions after subtraction of precursor contributions. A significant enhancement in the total measured excitation functions over their total theoretical predictions for the evaporation residues \(^{157,155}\text{Dy} (\text{αxn})\) and \(^{155}\text{Tb} (\text{αpxn})\) produced in α-emitting channels has been observed. This enhancement is attributed due to the presence of break-up of the incident projectile \(^{16}\text{O}\) into α clusters (i.e., break-up of \(^{16}\text{O}\) into \(^{12}\text{C} + \alpha\)) and incomplete fusion of projectile \(^{16}\text{O}\) with target \(^{148}\text{Nd}\) at these low energies. A comparison of the present data with earlier measurements indicates that the ICF probability depends on Coulomb factor \((Z_P Z_T)\) along with target deformation \((T_\beta^2)\). However, more systematic study on same Z spherical and deformed targets with same projectile at low energy is required to understand the role of target deformation on incomplete fusion dynamics.

**Keywords**: Complete and incomplete fusion, Offline γ-ray spectrometry, Stacked foil activation technique, Excitation functions, Target deformation

1 Introduction

Comprehensive studies on heavy ion induced reaction have shown that the complete fusion (CF) and incomplete fusion (ICF) processes are the dominant modes at energy below 10 MeV/A and above the Coulomb barrier\textsuperscript{1-4}. In the interaction of projectile with target, CF occurs when the projectile completely fuses with the target nucleus, forming a highly excited compound nucleus and it decays through the low energy light nuclear particles and/or γ-rays. However, the projectile may also breaks-up into its fragments and one of the fragment fuses with target while remnant behaves as spectator. This process is known as ICF. The first experimental evidence of ICF was given by Britt and Quinton\textsuperscript{5}. Major advancement on the study of ICF dynamics took place after the pioneering work of Inamura \textit{et al} \textsuperscript{6}. They observed the break-up of projectile like \(^{12}\text{C}, ^{14}\text{N}\) and \(^{16}\text{O}\) into α-particles using particle-gamma coincidence technique. Various efforts have been made to probe the dependence of ICF on different entrance channel parameters\textsuperscript{7-9}. Studies done by some investigators show that the ICF dynamics depends on Coulomb factor \((Z_P Z_T)\)\textsuperscript{10,11} and deformation of target \((T_\beta^2)\)\textsuperscript{12,13}. However, no definite conclusion has been established yet regarding the dependence of ICF on these parameters.

Several investigators have proposed the theoretical models to explain the ICF dynamics. The Sumrule model of Wilczynski \textit{et al} \textsuperscript{14}. The break-up fusion (BUF) model of Udagawa and Tamura \textsuperscript{15}, promptly emitted particle (PEP) model\textsuperscript{16}, hot spot model\textsuperscript{17} and multistep direct reaction model\textsuperscript{18} are some of the widely used models. These existing models can satisfactorily predict the measured ICF data at energy above 10 MeV/A. However, the non availability of any theoretical model below this energy makes the study of ICF dynamics still an active area of investigation.

There are some experimental techniques to probe the CF and ICF dynamics (i) excitation function (EFs), (ii) forward recoil range distributions (RRDs) (iii) forward angular distributions (FADs) (iv) kinetic and velocity spectra and (v) spin distribution (SDs)
measurements of evaporation residues. In the present work, measurements of excitation functions of evaporation residues has been done for the system $^{16}\text{O} + ^{148}\text{Nd}$ in the beam energy range $\approx$3-7 MeV/A. The measured excitation functions have been compared with the theoretical cross-sections of statistical model code$^{19}$ PACE-4. An attempt has been made to obtain the ICF contribution for the present system in this energy regime. Further, a systematic study has been done to understand the dependence of ICF dynamics on coulomb factor ($Z_PZ_T$) and deformation of target. The present paper is organized as follows; experimental details are given in section 2, results and discussions are presented in section 3. Finally, summary and conclusions of the present work are discussed in section 4.

2 Experimental Details

The present experiment has been performed using 15 UD Pelletron accelerator facilities at Inter University Accelerator Centre (IUAC), New Delhi, India. This experiment was done using General purpose scattering chamber (GPSC) coupled with in-vacuum transfer facility (IVTF). This facility has been utilized to minimize the time lapse between stop of irradiation and starting of counting. In these measurements, stacked foil activation technique has been employed. Targets of $^{148}\text{Nd}$ (Enrichment $\approx$98.4%) were prepared by vacuum evaporation technique at target development laboratory of IUAC, New Delhi. The target material was deposited on aluminium (Al) backing of thickness $\approx$1.2–1.7 mg/cm$^2$. These Al-backing foils were prepared by rolling method. The thickness of Al-backings was measured by $\alpha$-particle transmission$^{20}$ (using $^{241}\text{Am}$ source) as well as weighing method. To prevent the oxidizing process of $^{148}\text{Nd}$, a thin layer of carbon ($\approx$10 $\mu$g/cm$^2$) was deposited just after the deposition of the Nd material without breaking the vacuum of high vacuum evaporation chamber utilizing multi-crucible slots. Thickness of the targets used in the stack was lying in the range $\approx$100–300 $\mu$g/cm$^2$. Further, to estimate the thickness of different target samples, Rutherford back scattering (RBS)$^{20}$ measurement have been done. The purity of the target material was checked using Energy dispersive X-ray spectroscopy (EDXS) technique$^{20}$. A stack of seven $^{148}\text{Nd}$ targets with Al-backings was irradiated by $^{16}\text{O}^+$ beam of energy $\approx$100 MeV. The stack was irradiated for about 10 h due to the interest of half-lives of the evaporation residues. Beam current was monitored $\approx$2 pnA during the irradiation of targets. Energy loss of the incident beam on successive targets has been calculated using software SRIM-2008$^{21}$. The activities produced in the irradiated samples were recorded immediately after the irradiation for each target at different time intervals by using 100 c.c. n-type high purity germanium (HPGe) detector connected to a PC through CAMAC based data acquisition system. The software CANDLE$^{22}$ was used for the online data recording and offline analysis of the measured data. The energy and efficiency calibration of the HPGe detector was done using the standard $^{152}\text{Eu}$ $\gamma$-ray source of known strength. A typical calibrated $\gamma$-ray spectrum of $^{16}\text{O} + ^{148}\text{Nd}$ system at projectile energy $\approx$99.9 MeV is shown in Fig. 1. Different $\gamma$-ray peaks have been assigned to evaporation residues produced through CF and/or ICF dynamics. The ERs have been identified by observing their characteristic $\gamma$-rays and following their half lives in decay curve.

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Several factors are responsible for the uncertainties in the measured cross-sections. The main factors are: (i) the uncertainty due to the non-uniformity of the target, (ii) the uncertainty in the efficiency calibration of the HPGe detector, (iii) the error arising from the fluctuations in beam current and (iv) uncertainty due to the straggling effect of the projectile passing through the stack. The overall uncertainty from various factors was estimated to be $\geq$15%.

3 Results and Discussion

Excitation functions of the evaporation residues $^{161,159,157}\text{Er}$ ($\alpha$x$n$), $^{161-159}\text{Ho}$ ($\alpha$x$n$), $^{157,155}\text{Dy}$ ($\alpha$x$n$) and $^{155}\text{Tb}$ ($\alpha$x$n$) produced via complete and/or incomplete fusion have been measured in the $^{16}\text{O} + ^{148}\text{Nd}$ system in the energy range $\approx$3-7 MeV/A. Measured excitation functions of these ERs have been compared with the theoretical cross-sections of

![Fig. 1 – Typical $\gamma$-ray spectrum showing $\gamma$ lines of evaporation residues populated via CF and/or ICF reaction in $^{16}\text{O} + ^{148}\text{Nd}$ system at projectile energy 99.9 MeV.](image-url)
statistical mode code PACE-4, which uses Monte Carlo simulation procedure for the de-excitation of the compound nucleus and are found to agree well with the theoretical predictions. This code is based on Hauser-Feshbach theory. The angular-momentum projections are calculated at each stage of compound nucleus de-excitation and enable to determine the angular distribution of emitted particles. The angular-momentum conservation is explicitly taken into account at each step that the CF cross sections are calculated using bass formula\textsuperscript{23}. The optimization of input parameters has been done by achieving best fitting for the CF (xn/pxn) channels. In this code, level density parameter $a = A/K \text{ MeV}^{-1}$ is one of the important parameters, where $A$ is the mass number of the compound nucleus and $K$ is called the level density parameter constant, which affects the equilibrium components. The sum of measured excitation functions of the evaporation residues produced via xn and pxn channels have been plotted along with the sum of their PACE-4 predictions and shown in Fig. 2. In this figure, the total measured cross-sections of these ERs have been found to be in good agreement with the total PACE-4 predictions. This indicates that these ERs are populated mainly through CF process only. Further, the total measured cross-sections of ERs produced via $\alpha$xn and $\alpha$pxn channels have been plotted along with the sum of their PACE-4 predictions and shown in Fig. 3. A significant enhancement in the total measured excitation functions over their total theoretical predictions for the ERs produced through $\alpha$-emitting channels has been observed. This enhancement is attributed due to the presence of break-up of the incident projectile $^{16}\text{O}$ into $\alpha$ clusters (i.e., break-up of $^{16}\text{O}$ into $^{12}\text{C} + \alpha$) and incomplete fusion of projectile $^{16}\text{O}$ with target $^{144}\text{Nd}$ at these low energies.

ICF fraction for the present system has been estimated from the measured and theoretical cross-sections. The ICF fraction ($F_{\text{ICF}}$) is the measure of strength of ICF relative to total fusion (CF and ICF) cross-sections. The detailed description of determination of $F_{\text{ICF}}$ is given in literature\textsuperscript{24}. The dependence of ICF dynamics on Coulomb factor ($ZPZT$) and target deformation ($\beta^2$) has been investigated. In the present work, the ICF fraction for the present system along with some other systems from literature\textsuperscript{13, 25-31} has been taken for comparison at a constant value of $V_{\text{rel}}/c = 0.062$. The $F_{\text{ICF}}$ fractions have been plotted as a function of Coulomb factor ($ZPZT$) and $\beta^2$ as displayed in Figs 4 and 5.

![Fig. 2 – Sum of measured EFs of xn/pxn channels populated in $^{16}\text{O} + ^{144}\text{Nd}$ system along with their PACE-4 predictions at $K = 10$.](image2.png)

![Fig. 3 – Sum of measured EFs of $\alpha$xn/pxn channels populated in $^{16}\text{O} + ^{144}\text{Nd}$ system along with their PACE-4 predictions at $K = 10$.](image3.png)

![Fig. 4 – The incomplete fusion fraction ($F_{\text{ICF}}$) for the present system along with literature data\textsuperscript{13, 25-31} as function of $ZPZT$ at a constant value $V_{\text{rel}}/c = 0.062$. The solid lines are to represent the data for different projectiles.](image4.png)
The $\beta^T_2$ values have been adopted from the reference. Figure 4 shows that the ICF fraction increases linearly with Coulomb factor ($ZPZ_T$), separately for $^{16}$O and $^{12}$C projectiles. The solid lines are to guide the eyes.

As can also be seen from the Fig. 5 that the value of $F_{ICF}$ follows a nearly exponential which increase with deformation parameter ($\beta^T_2$). The rising rates of $F_{ICF}$ fraction are different for projectiles $^{16}$O and $^{12}$C. These observations indicate that the ICF fraction also depends on structure projectile affect ICF dynamics along with $ZPZ_T$ and deformation of the target. Finally, the present results emphasize that the ICF dynamics not only depends on a single entrance channel parameter, but it also depends on various entrance channel parameters namely: $ZPZ_T$, deformation parameter ($\beta^T_2$), etc.

4 Summary and Conclusions

In the present study, excitation functions of evaporation residues $^{161,159,158}$Er (xn), $^{161,159}$Ho (pxn), $^{157,155}$Dy (axn) and $^{153}$Tb (apxn) populated via CF and ICF dynamics in the system $^{16}$O + $^{148}$Nd at energy range ≈3-7 MeV/A have been measured. The measured EFs have been compared with theoretical predictions of code PACE-4. The measured EFs of evaporation residues populated via xn/pxn channels are found to be well reproduced with the statistical model predictions PACE-4, which indicate their production through CF only. A significant enhancement in the measured cross-sections over their theoretical predictions of PACE-4 for the evaporation residues populated through $\alpha xn/\alpha pxn$ channels has been observed. The enhancement is due to the break-up of projectile $^{16}$O into $^{12}$C + $^4$He followed by fusion of one of the fragments with the target nucleus $^{148}$Nd, i.e., incomplete fusion. Hence, it is inferred that incomplete fusion contributes significantly in the production of ERs at these beam energies. A systematic study has been done to investigate the dependence of ICF dynamics on various entrance channel parameters. The ICF fraction of the present system along with some other systems from literature has been found to increase linearly with coulomb factor ($ZPZ_T$), but it also increases exponentially with deformation parameter ($\beta^T_2$).

However, the rate of increase of ICF fraction is different for different projectiles, which indicates the effect of structure of projectile on ICF dynamics. These present results clearly show that the ICF dynamics does not affected by a single entrance channel parameter, but it also affected by various entrance channel parameters namely: $ZPZ_T$, deformation parameter ($\beta^T_2$) etc. The present results highlight the role of target deformation on ICF dynamics along with other parameters. The target deformation should also be considered as a powerful tool in the study of ICF dynamics at low projectile energy. Further, more systematic study involving same Z (spherical and deformed) targets with same projectile is required to get a definite conclusion on the role of target deformation on incomplete fusion dynamics at low projectile energy.

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