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Investigation of the role of break-up processes on the fusion of $^{16}$O induced reactions

Devendra P. Singh,1,* Unnati,1 Pushpendra P. Singh,1 Abhishek Yadav,1 Manoj Kumar Sharma,2 B. P. Singh,1,1 K. S. Golda,3 Rakesh Kumar,3 A. K. Sinha,4 and R. Prasad1

1Department of Physics, Aligarh Muslim University, Aligarh (UP) 202 002, India
2Department of Physics, S. V. College, Aligarh (UP) 202 001, India
3Inter-University Accelerator Center, Aruna Asaf Ali Marg, New Delhi 110 067, India
4UGC-DAE-CSR, Bidhan Nagar, Kolkata 700 098, India

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An experiment was carried out to explore heavy ion incomplete fusion reaction dynamics, within the framework of the break-up fusion model, at energies near and above the Coulomb barrier. Excitation functions for several radionuclides produced via $\alpha xn$, $pxn$, and $axn$ channels were measured in the $^{16}$O + $^{181}$Ta system at energies of $\approx$76–100 MeV. The experimental excitation functions were compared with those calculated using the theoretical model code PACE4. It was observed that excitation functions of $\alpha xn$ channels are in good agreement with theoretical predictions. However, a significant enhancement in the measured excitation functions of $\alpha$-emitting channels was observed and attributed to the incomplete fusion processes. The incomplete fusion fraction ($F_{icf}$) that gives the relative importance of complete and incomplete fusion processes was found to increase with energy. The results are discussed in terms of $\alpha$-cluster structure of the projectile on various fusion reactions.

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I. INTRODUCTION

For many years, the study of heavy ion (HI) induced reactions has been used as an important tool to understand the reaction dynamics and the decay characteristics of excited compound nuclei at energies near and above the Coulomb barrier (CB) [1–4]. It is now experimentally established that complete (CF) and incomplete fusion (ICF) are the most dominating modes of reaction processes at these energies [5–10]. In the case of CF, all the nucleons of the projectile and target nuclei lose their identity and form a single, excited complex system, which may eventually lead to a fully equilibrated compound nucleus (CN). The equilibrium state occurs as the composite system produces an intense mean field that prevents the escape of nucleons from the excited complex system and leads to complete thermalization. At later stages, the CN de-excites via emission of light nuclear particle(s) and/or the characteristic $\gamma$ rays. However, in case of ICF, as the projectile comes within the field of the target nucleus, it is assumed to break up into its fragments (predominantly into $\alpha$ clusters, in the case of the projectiles having an $\alpha$-cluster structure), where one of the fragments may get fused with the target nucleus leading to the formation of an excited incompletely fused composite (ICF) system with a mass and/or charge less than the CN formed via CF [7]. The unfused fragment flows in forward cone with almost projectile velocity. Further, it has also been observed that, apart from CF and ICF, pre-equilibrium (PE) emission of light nuclear particles may also take place at these energies before the thermalization of the composite system [11–15]. Recently, it has been observed that ICF becomes more and more dominant as the projectile energy increases [16–21]. The different modes of reactions can also be understood on the basis of driving input angular momenta imparted into the system. The CF occurs for the input angular momenta values $\leq l_{crit}$, as per the sharp cutoff approximation. However, at relatively higher projectile energies and/or at larger impact parameters, ICF starts influencing the CF. It may, further, be pointed out that the multitude of driving input angular momenta may vary with the projectile energy and/or with the impact parameter. However, there is no sharp boundary for the CF and ICF processes; both the processes have been observed below and/or above the limiting value of input angular momenta [22]. A few reports have indicated that ICF can selectively populate high spin states in the final reaction products at low bombarding energies and can be used as a spectroscopic tool as well [23,24]. The ICF reactions have been demonstrated to populate neutron-rich nuclei compared to conventional fusion-evaporation reactions, opening possibilities for the study of nuclei along the neutron-rich side of the line of stability [25].

A variety of dynamical models/theories, like the Break-up Fusion (BUF) model [26], the SUMRULE model [27], the Promptly Emitted Particles (PEPs) model [28], the EXCITON model [29], the Hot Spot model [30], the Multistep Direct Reaction theory [31], and the Overlap model [32–34], have been proposed to explain ICF dynamics. Apart from the aforementioned dynamical models, Mogenstern et al. [35,36] investigated the mass asymmetry dependence of the ICF contribution. The details of the above models are given in Ref. [20]. It may, however, be pointed out that these models correctly predict the magnitude of ICF, to some extent, in some cases at energies $\gtrsim$10 MeV/nucleon, but none of these models/theories is able to successfully explain the ICF data at energies of $\approx$4–7 MeV/nucleon. As such, the study of ICF is still an active area of investigation. Despite the existence of so many models, a clear picture of the mechanism of ICF is yet to emerge, particularly at relatively low bombarding energies, i.e., $\approx$4–7 MeV/nucleon, where the systematic study...
is available only for a few projectile-target combinations [5,20]. As such, for better understanding of ICF dynamics at low energies, excitation functions (EFs) for several radionuclides produced in the $^{16}$O+$^{181}$Ta system ($Z_1 Z_2 = 584$) have been measured in the projectile energy range $\approx$76–100 MeV. It may be pointed out that, the charge multiplication $Z_1 Z_2$ for the system is much less than 1600 and, therefore, the fission probability in this case is quite low [37]. Cavinato et al. [1] have also studied the same projectile-target combination and measured the EFs for the production of some isotopes of Tl, Hg, Au, Pt, Ir, Os, and Re at energies of $\approx$69–126 MeV. However, they have limited themselves to discussing the data concerning fusion reactions only and have not made any comment about ICF even for those reaction channels where $\alpha$ particles are emitted. In the present work, cross sections have been measured for those residues that may be populated via ICF processes as well. In the work of Cavinato et al. [1], a part of the data is obtained using the thick target-catcher technique and a part from the angular distribution. In the present work, up to 100 MeV, the cross sections have been measured at eight different energies using the thick target-catcher technique. Further, as already mentioned, the cross sections for several reactions expected to be populated via CF and/or ICF processes have been measured. The data set from Ref. [1], in general, agree with the present work in the overlapping energy range. In the present work, the $^{189,191}$Pt isotopes studied by Cavinato et al. [1] could not be detected because of long half-lives and low intensities of $\gamma$ radiations. Also, the cross sections for $^{190}$Hg could not be measured because the threshold for this reaction is above 100 MeV. Cavinato et al. [1] have not measured the cross sections for the individual reaction channels and have measured the cumulative cross sections for Hg and Pt isotopes. In addition to the work presented in Ref. [1], the cross sections for several Tl isotopes populated by xn channels ($^{194,195}$Tl$^m$, $^{194,195}$Tl, $^{193}$Tl$^m$, $^{192}$Tl$^m$, and $^{192}$Tl$^m$) have been measured in the present work, which could not be measured by Cavinato et al. [1]. In view of the above, the present work not only supplements the data of earlier work [1] but also provides a new cross-section database for several residues. Further, in the present work, an attempt has also been made to estimate the relative contribution of CF and ICF to study the influence of ICF on CF processes. This article is organized as follows: a brief description of the experimental procedure is given in Sec. II, comparison and analysis of the experimental data with the theoretical model predictions is presented in Sec. III along with the results and their interpretation. The conclusions drawn from the present study are given in the last section.

II. EXPERIMENTAL PROCEDURE

The experiment was performed using an $^{16}$O$^+$ beam delivered from the 15UD-Pelletron Accelerator at the Inter-University Accelerator Centre (IUAC), New Delhi, India. Targets of spectroscopically pure $^{181}$Ta ($\approx$99.99%) of thickness $\approx$1.5 mg/cm$^2$ were prepared at the target laboratory of IUAC, using the rolling technique. To trap the recoiling products produced via different reaction processes, Al catchers of appropriate thickness were placed after each target. The thickness of each target and catcher foil was separately measured by weighing and also by the $\alpha$-transmission method. The $\alpha$-transmission method is based on the measurement of the energy lost by 5.487 MeV $\alpha$ particles (obtained from standard $^{241}$Am source) while passing through the target material. Irradiations were carried out in the General Purpose Scattering Chamber (GPSC), which has an in-vacuum transfer facility (ITF). The targets along with the Al catchers in the form of a stack were placed normal to the beam direction, so that the recoiling products could be trapped in the catcher foils and there would be no loss of activity. The experimental setup (target-catcher foil arrangement) was similar to that given in Ref. [20]. Three stacks, each of four foils, three foils, and one foil, respectively, were irradiated at energies of $\approx$100, 98, and 88 MeV to cover a wide energy range. Keeping in view the half-lives of interest, irradiations were carried out for $\approx$8–10 h for each stack. The Pelletron crew provided a constant beam current $\approx$50 nA throughout the irradiations. The beam flux was calculated using the total charge collected in the Faraday cup, which was placed behind the target-catcher foil assembly. The activities produced after irradiation were recorded using a precalibrated, High Purity Germanium (HPGe) detector of

![FIG. 1. An observed $\gamma$-ray spectrum of a $^{181}$Ta sample irradiated by an $\approx$100 MeV $^{16}$O$^+$ beam.](image-url)
TABLE I. List of final reaction products along with populated channels and their spectroscopic properties.

<table>
<thead>
<tr>
<th>Residue</th>
<th>T_{1/2}</th>
<th>J^+</th>
<th>E_{γ} (keV)</th>
<th>I_{γ} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>194TI(3n)</td>
<td>32.8 min</td>
<td>7^+</td>
<td>636.1</td>
<td>99</td>
</tr>
<tr>
<td>194TI(3n)</td>
<td>33 min</td>
<td>2^-</td>
<td>636.1</td>
<td>15.3</td>
</tr>
<tr>
<td>194TI(4n)</td>
<td>2.1 min</td>
<td>9/2^+</td>
<td>365.0</td>
<td>90.1</td>
</tr>
<tr>
<td>194TI(4n)</td>
<td>21.6 min</td>
<td>1/2^+</td>
<td>324.4, 1044.7</td>
<td>15.2, 8.99</td>
</tr>
<tr>
<td>192TI(5n)</td>
<td>10.6 min</td>
<td>7^-</td>
<td>422.9</td>
<td>31.1</td>
</tr>
<tr>
<td>192TI(5n)</td>
<td>9.6 min</td>
<td>2^-</td>
<td>422.9</td>
<td>31.1</td>
</tr>
<tr>
<td>193Hg(p3n)</td>
<td>3.8 h</td>
<td>3/2^-</td>
<td>381.6, 539.0</td>
<td>11.0, 1.2</td>
</tr>
<tr>
<td>193Hg(p3n)</td>
<td>11.8 h</td>
<td>3/2^-</td>
<td>258.1</td>
<td>60.0</td>
</tr>
<tr>
<td>192Hg(p4n)</td>
<td>4.85 h</td>
<td>0^-</td>
<td>274.8</td>
<td>50.4</td>
</tr>
<tr>
<td>191Hg(p5n)</td>
<td>49 min</td>
<td>3/2^-</td>
<td>224.6, 241.2</td>
<td>17.4, 8.9</td>
</tr>
<tr>
<td>191Hg(p5n)</td>
<td>50.8 min</td>
<td>13/2^+</td>
<td>420.3, 578.7</td>
<td>17.9, 7.0</td>
</tr>
<tr>
<td>192Au(αn)</td>
<td>4.94 h</td>
<td>1^-</td>
<td>295.5, 316.5</td>
<td>22.7, 58.0</td>
</tr>
<tr>
<td>191Au(αza2n)</td>
<td>3.18 h</td>
<td>3/2^-</td>
<td>283.9, 399.8</td>
<td>6.3, 4.5</td>
</tr>
<tr>
<td>190Au(α3n)</td>
<td>4.28 min</td>
<td>1^-</td>
<td>295.3, 301.9</td>
<td>71.0, 25.1</td>
</tr>
</tbody>
</table>

100 c.c. active volume coupled to a PC through CAMAC based FREEDOM software [38]. The detector was calibrated using various standard γ sources, such as 60Co, 133Ba, and 152Eu, of known strengths. The efficiency of the detector was determined at various source-detector separations. The detail of efficiency determination is given elsewhere [20].

A typical γ-ray spectrum for the 16O + 181Ta system at ≈100 MeV is shown in Fig. 1, where various γ peaks corresponding to different reaction products populated via CF and/or ICF channels are indicated. Further confirmation of the identification of reaction products has been made by the decay curve analysis. Identified evaporation residues along with their important spectroscopic properties are given in Table I. A FORTRAN programme based on standard formulation given in Ref. [20] has been used to determine the production cross sections of the reaction products. The experimentally measured cross sections for the population of residues via CF and/or ICF processes are given in Tables II and III. The errors in these measurements may arise mostly because of (a) nonuniformity of the target foil, (b) uncertainty in the determination of the efficiency of the detector, (c) fluctuations in the beam current, (d) the solid angle effect, etc. Details of errors due to above-mentioned factors are given in Ref. [20]. Attempts were made to minimize the uncertainties due to all the above factors. The overall error in the present work is estimated to be ≤15%, including the statistical errors.

TABLE II. Experimentally measured cross sections for the residues populated in the interaction of 16O with the 181Ta system.

<table>
<thead>
<tr>
<th>Lab energy (MeV)</th>
<th>σ(194TI)(mb)</th>
<th>σ(194TI)(mb)</th>
<th>σ(193TI)(mb)</th>
<th>σ(193TI)(mb)</th>
<th>σ(192TI)(mb)</th>
<th>σ(192TI)(mb)</th>
<th>σ(193Hg)(mb)</th>
<th>σ(193Hg)(mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>76 ± 1.1</td>
<td>2 ± 0.2</td>
<td>2 ± 0.2</td>
<td>0.1 ± 0.01</td>
<td>26 ± 3.8</td>
<td>–</td>
<td>–</td>
<td>23 ± 3.5</td>
<td>8 ± 0.8</td>
</tr>
<tr>
<td>80 ± 1.5</td>
<td>6 ± 0.8</td>
<td>6 ± 0.8</td>
<td>0.2 ± 0.02</td>
<td>45 ± 6.8</td>
<td>22 ± 3.2</td>
<td>22 ± 3.2</td>
<td>47 ± 7.0</td>
<td>21 ± 2.1</td>
</tr>
<tr>
<td>85 ± 1.2</td>
<td>4 ± 0.5</td>
<td>4 ± 0.5</td>
<td>0.3 ± 0.03</td>
<td>68 ± 10.2</td>
<td>61 ± 9.1</td>
<td>61 ± 9.1</td>
<td>60 ± 8.9</td>
<td>30 ± 3.0</td>
</tr>
<tr>
<td>87 ± 1.0</td>
<td>3 ± 0.4</td>
<td>3 ± 0.4</td>
<td>0.2 ± 0.02</td>
<td>46 ± 6.9</td>
<td>44 ± 6.5</td>
<td>44 ± 6.5</td>
<td>49 ± 7.4</td>
<td>22 ± 2.2</td>
</tr>
<tr>
<td>88 ± 1.6</td>
<td>2 ± 0.2</td>
<td>2 ± 0.2</td>
<td>0.2 ± 0.02</td>
<td>44 ± 6.5</td>
<td>91 ± 13.7</td>
<td>91 ± 13.7</td>
<td>42 ± 6.2</td>
<td>24 ± 2.3</td>
</tr>
<tr>
<td>93 ± 1.1</td>
<td>2.5 ± 0.3</td>
<td>2.5 ± 0.3</td>
<td>0.1 ± 0.01</td>
<td>35 ± 5.2</td>
<td>184 ± 27.6</td>
<td>184 ± 27.6</td>
<td>29 ± 4.4</td>
<td>13 ± 1.3</td>
</tr>
<tr>
<td>97 ± 1.0</td>
<td>2 ± 0.3</td>
<td>1.5 ± 0.2</td>
<td>0.1 ± 0.01</td>
<td>15 ± 2.3</td>
<td>171 ± 25.5</td>
<td>171 ± 25.5</td>
<td>12 ± 1.7</td>
<td>8 ± 0.7</td>
</tr>
<tr>
<td>99 ± 0.9</td>
<td>1 ± 0.1</td>
<td>1 ± 0.1</td>
<td>0.1 ± 0.01</td>
<td>17 ± 2.5</td>
<td>222 ± 33.3</td>
<td>222 ± 33.3</td>
<td>10 ± 1.5</td>
<td>6 ± 0.5</td>
</tr>
</tbody>
</table>

aCross-section values give an upper limit.

III. RESULTS AND ANALYSIS OF DATA

To study the ICF reaction dynamics in the 16O + 181Ta system, the EFs for 194TI, 194TI, 193TI, 193TI, 192TI, 192TI, 192TI, 193Hg, 193Hg, 192Hg, 191Hg, 191Hg, 192Au, 191Au, and 192Au radionuclides expected to be populated via CF and/or ICF were measured. A list of reactions populating various residues, their half-lives, characteristic γ lines, etc., is given in Table I. In general, a residue populated via a specific channel often emits several γ rays of different energies. The cross section for the channel was determined from the measured intensities of several characteristic γ rays and the value quoted is the weighted average of cross sections obtained for these γ rays [39].

A. (16O, xn) channels

The measured EFs for residues populated via xn channels are shown in Fig. 2(a). Obviously these channels are populated only by CF. From the analysis of experimental data, activities corresponding to 3n, 4n, and 5n channels were identified. The identification was done on the basis of measured half-lives and γ-ray energies of the residues. It may be pointed out that in the case of 3n and 5n channels metastable and ground states of 194TI and 192TI are plotted. In both these cases, the metastable and ground states of the respective residues decay with γ rays of nearly the same energy and half-life. As such, the observed composite decay curves give the sum of both the states in each case. Individual cross sections were obtained by dividing the measured composite cross sections in the ratio of their γ-ray intensities [40,41]. 193TI are populated by a 4n channel. The metastable state of a half-life of ≈2 min decays to the ground state, which has a half-life of ≈22 min. Because counting of the irradiated samples was done after
In the case of \( pxn \) channels, there is no likelihood of ICF and, therefore, these channels are also populated by CF only like \( xn \) channels. Residues corresponding to \( p3n \), \( p4n \), and \( p5n \) channels have been identified through their characteristic \( \gamma \) rays and also by the respective half-lives. In the case of the \( p3n \) and \( p5n \) channels metastable and ground states of the residues are populated while in the case of the \( p4n \) channel only one state is formed. All the residues in the \( pxn \) cases decay independently with their respective half-lives and \( \gamma \) rays of known energies. The cross sections for these channels are plotted in Fig. 2(b) and are tabulated in Tables II and III. Note that in the case of \( pxn \) channels the residues may be populated both by independent formation and also by the decay of the higher charge isobar precursor as shown below:

\[
\begin{align*}
^{16}O + ^{181}Ta & \rightarrow ^{197}Tl^+ \rightarrow ^{193}Tl^+ + 4n; \\
^{193}Tl^+ & \rightarrow ^{193}Hg + \beta^+ / EC; \\
& \quad \text{(precursor decay)} \\
^{16}O + ^{181}Ta & \rightarrow ^{197}Tl^+ \rightarrow ^{193}Hg + p3n. \\
& \quad \text{(independent decay)}
\end{align*}
\]

Similarly, the population of residues \(^{192}Hg\) and \(^{191}Hg\) may also be expected via the independent decay as well as the precursor decay of the type:

\[
\begin{align*}
^{16}O + ^{181}Ta & \rightarrow ^{197}Tl^+ \rightarrow ^{192}Tl^+ + 5n; \\
^{192}Tl^+ & \rightarrow ^{192}Hg + \beta^+ / EC; \\
& \quad \text{(precursor decay)} \\
^{16}O + ^{181}Ta & \rightarrow ^{197}Tl^+ \rightarrow ^{192}Hg + p4n; \\
& \quad \text{(independent decay)}
\end{align*}
\]

Note that in the case of \( pxn \) channels the sum of cross sections (\( \Sigma \sigma_{pxn} \)) for all the populated residues produced via \( xn \) (\( x = 3, 4, \) and 5) channels is also shown in Fig. 2(a), indicating the initial rise in \( \Sigma \sigma_{pxn} \) values and then nearly saturating at higher energies.
and

\[ ^{16}\text{O} + ^{181}\text{Ta} \rightarrow ^{197}\text{Tl}^* \rightarrow ^{191}\text{Tl}^* + 6n; \]

\[ ^{191}\text{Tl}^* \rightarrow ^{191}\text{Hg} + \beta^+/EC; \]

\[ \text{(precursor decay)} \]

\[ ^{16}\text{O} + ^{181}\text{Ta} \rightarrow ^{197}\text{Tl}^* \rightarrow ^{1\91}\text{Hg} + p5n. \]

\[ \text{(independent decay)} \]

However, in the case of the \( p5n \) channel, the precursor \(^{191}\text{Tl}^*\), which may be produced by a \( 6n \) channel, is not likely to be produced in the present experiment on account of its higher threshold (\( \geq 100 \text{ MeV} \)). In the case of \( p3n \) and \( p4n \) channels, the contribution of precursor decay could not be determined because of either the incomplete decay or the unknown decay characteristics of the precursor. For example, in the case of the \( p4n \) channel, the cross sections for the independent decay of precursor formed by the \( 5n \) channel determined from its characteristic \( \gamma \) rays are found to be higher than the cross sections for residue \(^{192}\text{Hg}\) populated by the \( p4n \) channel. This may happen, if the precursor does not feed the residue \(^{192}\text{Hg}\) formed by the \( p4n \) channel. As such, the decay scheme of \(^{192}\text{Hg}\) and \(^{193}\text{Hg}\) needs further investigation. The cross-section values quoted in Tables II and III for these reactions also contain precursor contribution, if any, in the case of \( p3n \) and \( p4n \) channels.

In Fig. 2(b), the sum of cross sections for all measured \( pxn \) channels, denoted by \( \Sigma\sigma_{pxn} \), has been obtained by adding the measured cross sections for \( p3n \), \( p4n \), and \( p5n \) channels. To determine the total measured fusion cross section \( \Sigma\sigma_{CF} \) (expt), the sum of cross sections due to \( xn \) channels, i.e., \( \Sigma\sigma_{xn} \), and the sum of cross sections due to all measured \( pxn \) channels, i.e., \( \Sigma\sigma_{pxn} \), have been added. The total \( \Sigma\sigma_{CF} \) (expt) shown in Fig. 2(c) has been compared with \( \Sigma\sigma_{CF} \) (Th) obtained using the code PACE4 [42] with different values of level density parameters \( a (a = A/K) \). This code is based on statistical Hauser Fashback formalism followed by Monte Carlo simulations to determine the decay sequence of an excited compound nucleus. The code calculates the cross sections for a particular reaction using Bass formulation [43]. A detailed discussion of this code is given in one of our recent works [20]. However, for the sake of completeness, it may be pointed out that nuclear level density plays a central role in any statistical analysis of nuclear reactions. In this code the most sensitive parameter is the level density parameter (LDP) \( a (a = A/K) \), which mainly governs the equilibrium state. Here, \( A \) is the atomic mass number of the compound nucleus and \( K \) is a free parameter. The value of \( K \) may be varied to match the experimental data. As can be seen from Fig. 2(c), the \( \Sigma\sigma_{CF} \) (expt) is in good agreement with theoretical \( \Sigma\sigma_{CF} \) values. The fact that the measured fusion cross section \( \Sigma\sigma_{CF} \) (expt) could be reproduced satisfactorily by PACE4 predictions strengthens the confidence in the choice of input parameters. Also, a value of LDP \( a (a = A/8 \text{ MeV}^{-1}) \) has also been suggested by Cavina et al. [1] for nuclei far from the magic region. Further, the literature values [1] for fusion cross sections are found to agree well with the present measurements and are shown in Fig. 2(c).

FIG. 3. (Color online) (a) Measured EFs for \( \alpha xn \) (\( x = 1, 2, \) and 3) channels, (b) sum of the \( \alpha xn \) channels, measured as well as calculated using PACE4 for \( K = 8, 9, 10 \) (dotted, dashed, and solid lines, respectively), and (c) sum of \( \sigma_{CF} \) (all \( \alpha xn \) channels). In panels (a), (b), and (c), the spline-like lines joining the experimental data points are just to guide the eyes. The inset shows cross sections for the sum of both CF and ICF channels and for CF channels separately. The increasing difference, between the two curves in the inset, with energy indicates the dominance of ICF processes with energy.

C. \((^{16}\text{O}, \alpha xn)\) channels

In Fig. 3(a), the measured cross sections for the population of \(^{193}\text{Au} \) \( (x = 1, 2, \) and 3) isotopes via \( \alpha xn \) channels are shown. Note that in the case of \( \alpha xn \) channels, the residue may be formed in two ways: (i) by CF of \(^{16}\text{O} \) followed by the formation of an excited CN from which evaporation of neutrons and \( \alpha \) particles takes place, or (ii) the \(^{16}\text{O} \) ion breaks into \( \alpha + ^{12}\text{C} \) and \(^{12}\text{C} \) fuses with the target leaving an \( \alpha \) particle as a spectator. In this case the excited nucleus formed by the fusion of \(^{12}\text{C} \) may emit neutrons while de-exciting. Option (i) refers to CF and option (ii) to ICF. These modes may be
represented by the following equations.

\[ ^{16}\text{O}(^{12}\text{C} + \alpha) \rightarrow ^{12}\text{C} + ^{181}\text{Ta} \rightarrow ^{193}\text{Au}^* + \alpha. \]

The residue \(^{192}\text{Au}^*\) may be populated via CF and/or ICF channels as

(i) complete fusion of \(^{16}\text{O}\), i.e.,

\[ ^{16}\text{O} + ^{181}\text{Ta} \rightarrow ^{197}\text{Tl}^* \rightarrow ^{192}\text{Au}^* + \alpha + n, \]

(ii) incomplete fusion of \(^{16}\text{O}\), i.e.,

\[ ^{16}\text{O}(^{12}\text{C} + \alpha) + ^{181}\text{Ta} \rightarrow ^{193}\text{Au}^* + \alpha, \]

\[ ^{193}\text{Au}^* \rightarrow ^{192}\text{Au}^{*+} + n. \]

The residue \(^{191}\text{Au}^*\) may be populated via CF and/or ICF channels as

(i) complete fusion of \(^{16}\text{O}\), i.e.,

\[ ^{16}\text{O} + ^{181}\text{Ta} \rightarrow ^{197}\text{Tl}^* \rightarrow ^{191}\text{Au}^* + \alpha + 2n, \]

(ii) incomplete fusion of \(^{16}\text{O}\), i.e.,

\[ ^{16}\text{O}(^{12}\text{C} + \alpha) + ^{181}\text{Ta} \rightarrow ^{193}\text{Au}^* + \alpha, \]

\[ ^{193}\text{Au}^* \rightarrow ^{191}\text{Au}^{*+} + 2n. \]

Similarly, the residue \(^{190}\text{Au}^*\) may be populated via CF and/or ICF channels as

(i) complete fusion of \(^{16}\text{O}\), i.e.,

\[ ^{16}\text{O} + ^{181}\text{Ta} \rightarrow ^{197}\text{Tl}^* \rightarrow ^{190}\text{Au}^* + \alpha + 3n, \]

(ii) incomplete fusion of \(^{16}\text{O}\), i.e.,

\[ ^{16}\text{O}(^{12}\text{C} + \alpha) + ^{181}\text{Ta} \rightarrow ^{193}\text{Au}^* + \alpha, \]

\[ ^{193}\text{Au}^* \rightarrow ^{190}\text{Au}^{*+} + 3n. \]

The residue \(^{192}\text{Au}^*\) may also be populated via the decay of \(^{192}\text{Hg}\) via \(\beta^+\)/EC decay. Both \(^{192}\text{Au}^*\) (\(T_{1/2} = 4.94\) h) and \(^{192}\text{Hg}\) (\(T_{1/2} = 4.85\) h) have nearly the same half-lives. In this case, it has been possible to separate out the contribution from the decay of \(^{192}\text{Hg}\) populated via the \(p4n\) channel using decay analysis. It is known from the successive radioactive decay, if the daughter nucleus half-life (\(T_A\)) and the parent nucleus half-life (\(T_P\)) are nearly equal, as in the present case, such that \(T_A = T_P(1 + \delta)\), where \(\delta \ll 1\), then the activity ratio increases approximately linearly with time, so long as \(t < 2T_B/\delta\) [44], where \(T_B\) is the mean lifetime of the parent nucleus. To obtain the cross section of \(^{192}\text{Au}^*\), a curve between the lapse time and its production cross section was plotted at different times and also at different energies. To obtain the independent cross sections at each energy, plots for different lapse times were extrapolated at \(t = 0\) time using a least-square linear fitting method. The cross section at time \(t = 0\) is the independent cross section for the production of \(^{192}\text{Au}^*\). In Fig. 3(a), the cross sections deduced as mentioned above for the independent production of \(^{192}\text{Au}^*\) have been plotted. Here [Fig. 3(a)] the sum of cross sections for all measured \(\alpha n\) channels, i.e., \(\Sigma \sigma_{\alpha n}\) (expt), is also shown and is found to increase with energy. It has already been mentioned that all the \(\alpha\)-emission channels identified in the present work are expected to have significant contributions from ICF processes. To determine the contribution from ICF processes to the \(\alpha n\) channels, the measured \(\Sigma \sigma_{\alpha n}\) (expt) has been compared with the corresponding values calculated using the theoretical model code \textsc{pace}4, which is based on statistical CN theory. Because the code does not take ICF into consideration, the calculated cross sections for \(\Sigma \sigma_{\alpha n}\) with code \textsc{pace}4 have predictions based on the CF model only. In Fig. 3(b) a comparison of \(\Sigma \sigma_{\alpha n}\) (expt) has been made with \(\Sigma \sigma_{\alpha n}(\text{Th})\) calculated theoretically using the CF model for three different values of physically acceptable [45] level density parameters \((K = 8, 9, \text{and } 10)\). As can be seen from this figure, the \(\Sigma \sigma_{\alpha n}(\text{Th})\), with any of the reasonable parameters could not reproduce \(\Sigma \sigma_{\alpha n}(\text{expt})\) above 85 MeV. The measured \(\Sigma \sigma_{\alpha n}(\text{expt})\) agree very well with \(\Sigma \sigma_{\alpha n}(\text{Th})\) at 80 MeV. However, above this data point all the measured cross sections are found to be much higher as compared to those of theoretical predictions based on the \textsc{pace}4 model. The difference between the experimental and the theoretical values of \(\Sigma \sigma_{\alpha n}\) may be assigned to ICF and has been denoted by \(\Sigma \sigma_{\text{ICF}}(\text{expt})\). Further, the difference between \(\Sigma \sigma_{\alpha n}(\text{expt})\) and \(\Sigma \sigma_{\alpha n}(\text{Th})\) is found to increase with energy above 80 MeV, indicating the dominance of ICF processes at relatively higher energies, with maximum ICF contribution at the highest studied energy i.e., 100 MeV. Further, in Fig. 3(c) \(\Sigma \sigma_{\text{ICF}}\) obtained by subtracting \(\Sigma \sigma_{\text{ICF}}(\text{Th})\) \((K = 10)\) from measured \(\Sigma \sigma_{\alpha n}\) is been plotted as a function of energy. As can be seen from this figure, ICF production increases very rapidly with energy. In the inset of Fig. 3(c) \(\Sigma \sigma_{\text{ICF}}\) (total sum of cross sections for all measured channels) and \(\Sigma \sigma_{\text{CF}}\) are compared. As can be seen from Fig. 3(c) (inset), with the increase in energy the difference between \(\sigma_{\text{TF}}\) and \(\Sigma \sigma_{\text{CF}}\) continues to increase, indicating the dominance of ICF at relatively higher energies. In a complementary experiment [46], recoil ranges for the same residues have been determined to get information about the degree of linear momentum transfer and the relative contribution of CF and ICF channels. The relative contribution of CF and ICF channels obtained from the complementary experiment agree with the present data within the experimental uncertainties.

At energies above the CB, where \(E \gg V_0\), the classical formula of Weisskopf [47] for capture of charge particle by a nucleus is given by

\[ \sigma_{\text{CF}}(E) = \pi r_0^2(1 - V_0/E), \]

where, \(V_0\) is the value of CB and \(E\) is the energy in center of mass system. As such, if \(\sigma_{\text{CF}}\) (Exp) is plotted against \(1/E_{\text{c.m.}}\), it should be a linear curve. The deduced \(\Sigma \sigma_{\text{CF}}\) values from \(\Sigma \sigma_{\alpha n} + \Sigma \sigma_{\text{ICF}}\) and \(\Sigma \sigma_{\alpha n}(\text{Th})\) have been plotted as a function of \(1/E_{\text{c.m.}}\) in Fig. 4. A fit to the \(\Sigma \sigma_{\text{CF}}\) data points indicates a linear curve that cuts the \(x\) axis at the beam energy equal to CB. It may, however, be pointed out that a departure from linearity above CB may indicate the approach to and beginning of a quantal regime giving rise to subbarrier fusion. Further,
to study the dependence of ICF contribution on energy, for the presently studied system, the percentage fraction of ICF fusion cross section \( F_{ICF} \) has been plotted in Fig. 5 as a function of beam energy normalized to CB, along with several other literature values \([5,16,19,20]\). As can be seen from this figure, \( F_{ICF} \) increases with the increase in normalized beam energy for all the systems. To study the dependence of \( F_{ICF} \) on mass asymmetry, the percent \( F_{ICF} \) has also been plotted in Fig. 6 as a function of mass asymmetry at a constant value \( (E_{beam}/V_b = 1.38) \) of normalized beam energy. As can be seen from this figure, the \( F_{ICF} \) for the presently studied system is not following the expected trend shown for other systems involving \(^{16}\text{O}\) beam. The present \( F_{ICF} \) for \(^{16}\text{O} + ^{181}\text{Ta}\) is found to be significantly small. It may be because of the fact that in the present measurements several other \( \alpha \)-emission channels, e.g., \(2\alpha \) and \(3\alpha \) channels, could not be observed as the residues populated via these channels were either stable or short-lived and/or had very low \( \gamma \)-ray intensity. We propose to measure the contribution of these \( \alpha \)-emission channels in an in-beam experiment using the particle-\( \gamma \) coincidence technique, so that the present data may be supplemented.

IV. CONCLUSIONS

In the present work, EFs for the production of 14 radionuclides, \(^{192}\text{Ti}^*(3n)\), \(^{194}\text{Ti}^*(3n)\), \(^{193}\text{Ti}^*(4n)\), \(^{195}\text{Ti}^*(4n)\), \(^{192}\text{Te}^*(5n)\), \(^{192}\text{Te}^*(5n)\), \(^{193}\text{Hg}^*(5n)\), \(^{193}\text{Hg}^*(5n)\), \(^{192}\text{Hg}^*(5n)\), \(^{191}\text{Hg}^*(5n)\), \(^{191}\text{Hg}^*(5n)\), \(^{192}\text{Au}^*(\alpha n)\), \(^{191}\text{Au}^*(\alpha 2n)\), and \(^{190}\text{Au}^*(\alpha 3n)\), were measured. The experimental data were compared with the predictions of the theoretical code PACE4 based on a statistical model. The CF cross sections were found to agree well with PACE4 calculations over the entire energy range. A significant enhancement in the cross sections was observed, for \( \alpha \)-emitting channels, as compared to the theoretical PACE4 model predictions. The observed enhancement was attributed to the prompt break up of the projectile into \( \alpha \) clusters, with \(^{16}\text{O}\) into \(^{12}\text{C} + ^{4}\text{He}\) leading to the ICF process. As such, it may be concluded that apart from CF, ICF is also a process of greater importance even at these low energies and, hence, when predicting the total reaction cross sections, the ICF contribution should also be taken into consideration. Further, as expected \( \Sigma \sigma_{ICF} \) was found to increase with energy.

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[42] FREEDOM, data acquisition and analysis system designed to support the accelerator based experiments at the Nuclear Science Centre, New Delhi, India.
Observation of large incomplete fusion in $^{16}\text{O} + ^{103}\text{Rh}$ system at $\approx 3–5$ MeV/nucleon

Unnati Gupta a, Pushpendra P. Singh a, Devendra P. Singh a, Manoj Kumar Sharma a, Abhishek Yadav a, Rakesh Kumar b, B.P. Singh a,∗, R. Prasad a

a Accelerator Laboratory, Department of Physics, A.M. University, Aligarh-202002, India
b NP-Group, Inter-University Accelerator Center, PO Box No. 10502, Aruna Asaf Ali Marg, New Delhi-110067, India

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Abstract

Incomplete fusion of $^{16}\text{O}(\approx 3–5$ MeV/nucleon) with $^{103}\text{Rh}$ has been investigated using measurement and analysis of excitation functions. Some $\text{pxn}/\alpha\text{pxn}$-channels are found to have contribution from pre-cursor decay, which has been separated out from cumulative cross-section of evaporation residues. The $\text{xn}/\alpha\text{xn}$-channels are found to be satisfactorily reproduced with the predictions of PACE4 after subtraction of pre-cursor decay contribution, in general. Sizable enhancement in the experimental cross-sections has been observed for $\alpha$-emitting channels over the theoretical once, which may be attributed to the incomplete fusion. The percentage fraction of incomplete fusion has also been deduced, which seems to be sensitive for projectile energy, entrance channel mass-asymmetry and/or projectile structure. The present work deals with the competition of incomplete fusion with complete fusion even at $\approx 3–5$ MeV/nucleon for $^{16}\text{O} + ^{103}\text{Rh}$ system.

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* Corresponding author. Tel.: +91 941 2133929; fax: +91 571 2701001. E-mail address: bpsinghamu@gmail.com (B.P. Singh).
1. Introduction

In recent years, the study of reaction dynamics in heavy ion (HI) interactions has acquired central place in nuclear physics research [1–7]. The HI-induced reactions are widely different from light ion induced reactions due to large fusion barrier \( B_{\text{fus}} \) and availability of different \( \ell \)-bins. In favorable conditions (only if the projectile energy is comparable to the \( B_{\text{fus}} \)), associated input angular momentum \( (\ell) \) is supposed to be large enough to produce nuclei in extreme conditions (high excitation energy and spin). Since, the de-Broglie wavelength in HI-induced reactions is of the order of nuclear dimensions, therefore, the interaction may be explained by adopting semi-classical approach [8]. Classically, the interaction trajectories depending on different \( \ell \)-bins and/or impact parameters lying within the target dimensions may lead prominently to reaction processes like (i) complete fusion (CF), and (ii) incomplete fusion (ICF). In case of CF, with the collision trajectories \( 0 \leq \ell \leq \ell_{\text{crit}} \), the interacting partners may be trapped in the pocket of entrance channel potential involving all nucleonic degrees of freedom [9–11]. Consequently, the entire kinetic energy and linear momentum of the projectile are ultimately equally shared among all the constituents of the composite system leading to the fully equilibrated compound nucleus (CN). However, at relatively higher values of impact parameters for the collision trajectories (input angular momentum range) with \( \ell \geq \ell_{\text{crit}} \), the pocket in the entrance channel potential vanishes [12–14]. Therefore, the nuclear field of target nucleus is no longer strong enough to trap all the nucleons, consequently, the fractional momentum transfer takes place leading to the ICF process. As a result of ICF of projectile, (i) the CN is formed with less mass and charge as compared to the total mass and charge of interacting partners; (ii) the recoil velocity of the reaction products should be less than the complete fusion population and (iii) the angular distribution of ejectiles is expected to show maxima at forward angles. In case of ICF processes, the mass transfer occurs mostly from lighter to heavier partner, the feature observed more prominently for mass asymmetric systems as compared to mass symmetric systems [15–18].

To explain various ICF processes, several dynamical models like; Break-Up Fusion (BUF) model [19], SUMRULE model [20], Promptly Emitted Particles (PEPs) model [21], EXCITON model [22], etc., have been proposed. In SUMRULE model, Wilczyński et al. [20] suggested that ICF is mainly confined to the \( \ell \)-space above \( (\ell_{\text{crit}}) \) for CF, and originate from peripheral interactions or non-central collisions. The non-central nature of ICF dynamics has also been emphasized by Trautmann et al. [14], and Inamura et al. [23,24]. The BUF-model [19] of Udagawa and Tamura is based on the Distorted Wave Born Approximation (DWBA), in which the projectile is assumed to break-up into constituent alpha-clusters (e.g., \(^{16}\text{O}\) may break-up into \(^{12}\text{C} + \alpha \) and/or \(^{8}\text{Be} + ^{8}\text{Be}\)) within the nuclear field range of target nucleus. One of the fragments may get fused with target nucleus (depending on the available \( \ell \)-value) [19], while the remnant behaves like a spectator dominantly ejected in the forward cone. According to PEP model [21], the nucleons transferred from projectile to the target nucleus may get accelerated in the nuclear field of target nucleus and consequently acquire extra velocity to escape before equilibration. The EXCITON model assumes that the projectile nucleons undergo a series of collisions with the target nucleus creating particle-hole excitations, which de-excite by emitting fast nuclear particles [22]. Apart from these, Overlap model [25–27] and Multistep Direct Reaction theory [28] have also been proposed, and Morgenstern et al. [17,29], correlated the probability of ICF reactions to the entrance channel mass asymmetry. It may, further, be pointed out that the aforementioned models/theories, generally, have been used to fit the experimental data obtained at energies \( E/A \geq 10.5 \text{ MeV} \) or so, but no satisfactory comparison has been made at relatively low bombarding energies (i.e., 5–7 MeV/nucleon). As such, due to the unavailability of any re-
liable theoretical model to fit the experimental data obtained at energies $\approx 5–7$ MeV/nucleon, the study of ICF is still an active area of investigations. Furthermore, there is a renewed interest in the study of ICF dynamics after observation of these reactions at relatively low bombarding energies [30–33]. Moreover, the ICF reactions are considered to be a promising route to produce high spin states even at low bombarding energies [34,35]. Moreover, some important issues associated with ICF dynamics at energies $\leq 7$ MeV/nucleon are (i) the onset of ICF at energies slightly above the $B_{\text{fus}}$, and (ii) the relative contributions of CF and ICF processes, which have not yet been fully explored or limited up to a few projectile–target combinations only. Therefore, in order to have better understanding of ICF processes, a comprehensive study of excitation functions (EFs), forward recoil range distributions (RRDs) and angular distributions (ADs) of recoils in HI induced reactions have been undertaken by our group [30,36–38]. In the present work, the measurement of EFs for several radio-active isotopes produced in $^{16}\text{O} + ^{103}\text{Rh}$ system have been performed in the energy range $\approx 50–85$ MeV. Similar measurements for the same system have also been performed by Z. Buthelezi et al. [39], at energies $\approx 40–400$ MeV. However, in the present work, precursor decay contributions (if any) in the production of several reaction products have also been estimated from cumulative cross-sections of residues, which has not been considered in Ref. [39]. As such, the present work may serve as the complement and/or as, at some places, supplement to the above measurements at energies $\approx 50–85$ MeV. The present paper is organized as follows: the experimental details and methodology are given in Section 2. However, the production cross-section measurement and estimation of independent cross-section from cumulative cross-section are described in Section 3. The analysis of experimentally measured EFs with the predictions of statistical model code PACE4 are given in Section 4. The influence of ICF on CF and its dependence on projectile energy and mass-asymmetry of interacting partners are presented in Section 4.1, while, Section 5 deals with the summary and conclusions of the present work.

2. Experimental details and methodology

Experiments have been performed at the Inter-University Accelerator Centre (IUAC), New Delhi, India. The targets of $^{103}\text{Rh}$ of thickness $\approx 2.0$ mg/cm$^2$ were prepared from the spectroscopically pure foils of natural Rhodium ($^{103}\text{Rh}$) employing rolling technique. The thickness of each target was determined by $\alpha$-transmission method. The targets were fixed on Al-holders of $1.2 \times 1.2$ cm$^2$ size and concentric hole of $\approx 10$ mm diameter. In order to cover a wide energy region in a single irradiation, energy degradation technique has been used. Two stacks, each containing three $^{103}\text{Rh}$-target foils were irradiated by $^{16}\text{O}^{7+}$ beam at energies $\approx 80$ and 85 MeV, separately. Typical stacked foil arrangement used for EF measurements is shown in Fig. 1. The successive targets in the stack are backed by Al-catchers of appropriate thicknesses, so that the recoiling nuclei may be trapped in the catcher foil thickness itself. The incident energy on each target-catcher foil assembly in a stack has been estimated using code SRIM, based on stopping power formulation. The errors in the incident energies on each foil have been calculated as the energy loss at half thickness of the target/catcher foils. The first foil of the first stack at highest beam energy (i.e. $\approx 85$ MeV) has an energy uncertainty of $\pm 2.06$ MeV, however, the last foil of the second stack has the uncertainty of $\pm 2.77$ MeV, calculated as discussed above. Irradiations have been carried out in the General Purpose Scattering Chamber (GPSC), with a beam current $\approx 10$ pnA. Keeping in view, the half-lives of interest irradiations have been carried out for $\approx 8$ hours. After the irradiation, the target-catcher foil assembly has been taken out from the scattering chamber with the help of invacuum transfer system. The activities produced in the
samples were recorded by a pre-calibrated HPGe detector of 100 c.c. active volume coupled to a CAMAC based software FREEDOM.\textsuperscript{1} The detector used in this experiment was pre-calibrated for energy and efficiency using various standard $\gamma$-sources, viz., $^{60}$Co, $^{133}$Ba and $^{152}$Eu at different source-detector separations. The target-detector separation was suitably adjusted so as to keep the dead time < 10\%. In order to detect and follow the longer lived residues, the counting of irradiated samples has been done for a week or so. A relevant portion of a typical $\gamma$-ray spectra of the $^{16}$O + $^{103}$Rh system at $\approx 82.94 \pm 2.06$ MeV is shown in Fig. 2. The residues were identified by their characteristic $\gamma$-rays as well as by decay curve analysis. A list of residues, $\gamma$-ray energies, abundances, etc., used in the present work are tabulated in Table 1. The spectroscopic data has been taken from the “Table of Radioactive Isotopes” by Browne and Firestone [40].

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\textsuperscript{1} FREEDOM, Data acquisition and analysis system designed to support the accelerator based experiments at the Nuclear Science Centre, New Delhi, India (2000).
3. Measurement of production cross-sections

The projectile energy dependent reaction cross-sections $\sigma_r(E)$, for different radio-nuclides have been determined using the following expression [48]:

$$\sigma_r = \frac{C_{t=0}}{N_0 \theta \phi G_e K[1 - \exp(-\lambda t_1)]}$$ (1)

where

- $C_{t=0} = \text{The count rate just after the irradiation, i.e., at zero time,}$
- $N_0 = \text{Initial number of nuclei in the target sample,}$
- $\theta = \text{Branching ratio of the characteristic } \gamma\text{-rays assigned to different reaction products,}$
- $\phi = \text{The incident beam flux,}$
- $G_e = \text{Geometry dependent efficiency of the HPGe detector,}$
- $K = (1 - \exp(-\mu d))/\mu d = \text{The self absorption correction factor for the } \gamma\text{-rays in the material of the sample of thickness } d(\text{gm/cm}^2) \text{ and the absorption coefficient } \mu(\text{cm}^2/\text{gm}),$
- $\lambda = \text{Decay constant of the radio-nuclides, and}$
- $t_1 = \text{Time of irradiation.}$
Further, the errors in the measured production cross-sections of different radio-nuclides may arise due to various factors like: (i) Non-uniform thickness of the samples, i.e., the inaccurate estimate of foil thickness may lead to the uncertainty in the determination of the number of target nuclei in the sample. However, in order to check the uniformity of the sample, thickness of each sample was measured at different positions by $\alpha$-transmission method. The error in the thickness of the sample is estimated to be $\approx 1\%$. (ii) Fluctuations in the beam current may result in the variation of incident flux, as such proper care has been taken to maintain the beam current constant so that the error due to beam current fluctuations may be minimized. (iii) Uncertainty in the determination of geometry dependent spectrometer efficiency. The error in the efficiency determination due to the statistical fluctuations in counts is estimated to be less than 2\%. (iv) The loss of product nuclei recoiling out of the target may introduce large errors in the measured cross-sections. The thickness of the catcher foils used in the present work were sufficient to stop even the most energetic residues. However, in the present measurements both the sample and the catcher foils were counted together and hence, the losses due to the recoiling of nuclei is avoided. (v) Dead time of the spectrometer was kept less than 10\% by suitably adjusting sample-detector distance. The overall errors including statistical errors are estimated to be $\leq 15\%$, excluding the uncertainty in branching ratio, decay constant, etc., which have been taken from the “Table of Radioactive Isotopes” [40].

### 3.1. Estimation of independent cross-section from cumulative cross-sections

In the present work, the EFs for several radio-nuclides $^{117}$g Te(pn), $^{116}$Te(p2n), $^{115g, m}$Te(p3n), $^{114}$Te(p4n), $^{117}$Sb(2p), $^{116g, m}$Sb(2pn), $^{115}$Sb(2p2n), $^{110}$Sn(αp4n), $^{111g}$In(2α), $^{110g, m}$In(2αn), $^{109g}$In(2α2n), $^{108g, m}$In(2α3n), $^{106m}$Ag(3αn), $^{104g}$Ag(3α3n) and $^{103g}$Ag(3α4n) expected to be populated via CF and/or ICF have been measured. Some of the pxn/αpn-channels are found to have contribution from higher charge isobar pre-cursor through $\beta^+\text{-emission and/or electron capture (EC), where the cumulative cross-sections have been measured. For such cases, if the half-life of the pre-cursor is considerably smaller than that of the daughter residue, the independent production cross-sections ($\sigma_{\text{ind}}$) have been estimated from the cumulative production cross-sections ($\sigma_{\text{cum}}$). The $\sigma_{\text{cum}}$ of a given residue is the sum of $\sigma_{\text{ind}}$ and the cross-section for the independent production of its pre-cursor $\sigma_{\text{pre}}$ multiplied by a numerical coefficient $F_p$, i.e.,

$$\sigma_{\text{cum}} = \sigma_{\text{ind}} + F_p \sigma_{\text{pre}}.$$  

(2)

The value of $F_p$ depends on the branching ratio $P_p$ for pre-cursor decay to the residue and is given by

$$F_p = P_p \frac{T_{\text{ind}}^{1/2}}{T_{\text{ind}}^{1/2} - T_{\text{pre}}^{1/2}},$$

(3)

here $T_{\text{pre}}$ and $T_{\text{ind}}$ are the half-lives of the pre-cursor and the residue. In this way the cumulative cross-section is given by

$$\sigma_{\text{cum}} = \sigma_{\text{ind}} + P_p \frac{T_{\text{ind}}^{1/2}}{T_{\text{ind}}^{1/2} - T_{\text{pre}}^{1/2}} \sigma_{\text{pre}}.$$  

(4)

As a representative case, the evaporation residue $^{117g}$Te (Fig. 3(a)) is likely to be populated via CF of $^{16}$O with the $^{103}$Rh nucleus forming the composite system $^{119}$I$^*$ followed by the evap-
The lines represent the theoretical calculations done using code PACE4 for different values of $K$, where a value of $K = 8$ is found to be the best choice for the studied system. The solid (black) triangle and solid (red) circles, respectively, represent cumulative ($\sigma_{\text{cum}}$) and independent ($\sigma_{\text{ind}}$) production cross-section of residues. Measured EFs have been compared with Ref. [39], the experimental data points taken from Ref. [39], are given by solid star. Ground and metastable states (if any) are given in self explanatory manner in the figures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)

The same residue $^{117}\text{Te}$ may also be populated by the $\beta^+$ emission and/or electron capture (EC) of higher charge pre-cursor isobar $^{117}\text{I}$. As such, the measured activity of residues $^{117}\text{Te}$ may have contribution from the decay of its pre-cursor isobar also. The values of branching ratios required for obtaining the coefficient $F_p$ are taken from...
Ref. [41]. Using the above formulation, the cumulative yield ($\sigma_{\text{cum}}$) and independent yield ($\sigma_{\text{ind}}$) for $^{117}$Te are related by the equation

$$\sigma_{\text{cum}}(^{117}\text{Te}) = \sigma_{\text{ind}}(^{117}\text{Te}) + 1.03\sigma_{\text{pre}}(^{117}\text{I}).$$  \hspace{1cm} (5)

Here $\sigma_{\text{pre}}(^{117}\text{I})$ is the independent yield of the pre-cursor.

In the similar way, the independent production cross-sections for other residues have also been deduced from the $\sigma_{\text{cum}}$ and $\sigma_{\text{pre}}$ contributions. The independent production cross-sections have been compared with statistical model code PACE4 [43], and are found to agree reasonably well with the theoretical calculations. The optimization of input parameters has been done by achieving best fitting for CF products ($xn/$pxn-channels), details of the code PACE4 (which is the modified version of PACE2) and data analysis are discussed in the following section.

4. Analysis of EFs with PACE4

The calculation of theoretical production cross-sections for the evaporation residues populated via CF channels have been obtained using code PACE4. The code PACE4 (which is a revised version of PACE2) is based on Hauser–Feshbach approach. It may be pointed out that the ICF and PE-emission are not taken into consideration in this code. The cross-sections for evaporation residues are calculated using Bass formula [42]. The de-excitation of the compound nucleus is followed by Monte Carlo procedure. The projections of angular momentum are calculated at each stage of de-excitation, which enables the determination of angular distribution of the emitted particles. The optical model parameters for neutrons, protons and $\alpha$-particles are used as default in the code [43]. The $\gamma$-ray strength functions for $E_1$, $E_2$ and $M_1$ transition were taken from tables of Endt [44]. This code has been modified to take into account the excitation energy dependence of level density parameter using the prescription of Kataria et al. [45].

The partial cross-section ($\sigma_\ell$) for the formation of CN at angular momentum $\ell$ and specific bombarding energy $E$, is given by

$$\sigma_\ell = \frac{\lambda^2}{4\pi} (2\ell + 1) T_\ell. \hspace{1cm} (6)$$

Here $\lambda$ is the reduced wavelength. The transmission coefficients $T_\ell$ may be given by the expression

$$T_\ell = \left[ 1 + \exp\left( \frac{\ell - \ell_{\text{max}}}{\Delta} \right) \right]^{-1} \hspace{1cm} (7)$$

where $\Delta$ is the diffuseness parameter and $\ell_{\text{max}}$ the maximum value of $\ell$ detained by total fusion cross-section,

$$\sigma_F = \sum_{\ell=0}^{\infty} \sigma_\ell. \hspace{1cm} (8)$$

The transmission coefficients for the evaporation of light particles (n, p and $\alpha$) during the de-excitation are obtained by optical model calculations [46,47]. The fission decay mode may be considered using a rotating liquid fission barrier routine [43]. As a typical example, at 85 MeV incident beam energy the values of $\ell_{\text{max}}$ and $\Delta$ are $\approx 63h$ and $\approx 2h$. The level density in this code is calculated using the expression $a = A/K$, where $A$ is the atomic mass number and $K$ is a parameter called level density parameter. In these calculations $K$ is an important parameter and affects the equilibrium component. As such, in order to show the effect of variation of $K$ on
Fig. 4. Experimentally measured and theoretically calculated EFs for different residues populated via CF and/or ICF ($\alpha x n/2\alpha x n$-channels) in $^{16}O + ^{103}Rh$ system at $\approx 46-85$ MeV. Dark circles represent the experimental cross-sections. The enhancement over the theoretical model predictions may be attributed to ICF processes.

calculated EFs, different values of $K$ (8, 9 and 10) have been tested, and are shown in Figs. 3(a)–(f) and 4(a)–(d). It may be pointed out that, it might be possible to predict all the EFs with different values of parameters of the code for individual channels. However, it is not reasonable from the physics point of view. Further, a value of $K \geq 10$ may give rise to the anomalous effect in the particle multiplicity. In the present work, a value of $K = 8$ is found to give a satisfactory reproduction of experimental data for CF-channels within the experimental uncertainties.

The metastable state of $^{117}$Te could not be observed due to its very short half-life ($\approx 103$ ms). As can be seen from the Figs. 3(a)–(f), the experimentally measured EFs for radio-nuclides $^{117g}$Te(pn), $^{116}$Te(p2n), $^{115g,m}$Te(p3n), $^{115}$Sb(2p2n), $^{117}$Sb(2p) and $^{114}$Te(p4n) are satisfactorily reproduced by theoretical model predictions within the experimental uncertainties, and may be assumed to be populated via CF (as there is no alpha-particle in exit-channels). Further, in some cases (Fig. 3) experimental data is somewhat enhanced as compared to the theoretical model predictions. In such cases the same residues may be populated via two different modes of decay, viz., (i) directly from the decay of CN (independent production), and (ii) through the $\beta^+/EC$ decay of higher charge isobar pre-cursors. As such, the experimentally measured production cross-section
is expected to be the admixture of two different decay modes as mentioned above. The independent cross-section ($\sigma_{\text{ind}}$) has been separated out from cumulative cross-section ($\sigma_{\text{cum}}$) using prescription of Cavinato et al. [31], discussed in Section 3.1 of this paper. As can be seen from the figures, there is a reasonable agreement between theoretical and experimental EFs after subtracting the contribution coming from pre-cursor decay. However, in Fig. 3(b) the higher values of cross-sections in the tail portion of the EFs may be an indication of pre-equilibrium-emission at higher energies [49–52], which is not taken into account in these calculations.

4.1. Interpretation of experimental results

The fact that the measured EFs for almost all predominantly populated CF-channels could be reproduced by PACE4 predictions, gives confidence to the choice of input parameters of theoretical model code. Therefore, same set of input parameters has also been used to fit the EFs of all $\alpha$-emitting channels. As can be observed from Figs. 4(a)–(d), the experimentally measured EFs are relatively higher as compared to the theoretical predictions. Since the theoretical model code PACE4 does not take ICF into account, therefore the enhancement in the experimentally measured production cross-sections may be attributed to the contribution coming from ICF of $^{16}$O with target nucleus. As such, these residues are expected to be populated both via CF and/or ICF of projectile. The production of these residues is assumed to be originated from the successive decay of CN followed by entire projectile fusion in CF process, and/or via fusion of $^{12}$C/$^{8}$Be from $^{16}$O-projectile in ICF processes leading to $^{115}$Sb$^*/^{111}$In$^*$, respectively. The final reaction products appear after emission of a few nucleons from $^{115}$Sb$^*/^{111}$In$^*$ (incompletely fused composites). In this case it has been assumed that $^{16}$O projectile breaks-up into its $\alpha$-clusters, viz., $^{12}$C + $\alpha$ and/or $^{8}$Be + $^{8}$Be, a part of projectile fuses with $^{103}$Rh, while remnant moves in forward cone with almost projectile velocity. As can be seen from Fig. 4(c), the theoretically calculated EFs for $^{103}$Rh($^{16}$O, 2$\alpha$2n)$^{109}$In reaction is almost matching/slightly higher than the experimental data for all values of $K$, revealing very less/negligible contribution from ICF. It may, however, be pointed out that recoil range distribution measurement for this channel may give some clue about its population via CF only. Further, experimentally measured EFs for 3$\alpha$xn-channels ($x = 1, 3, 4$) are shown in Fig. 5. The theoretical calculations give negligible cross-sections for these residues and hence are not shown in Fig. 5, meaning thereby, these residues are likely to be populated only via ICF. It may also be pointed out that no choice of physically reasonable parameters in theoretical calculations could reproduce the population of these residues.

Moreover, the reaction $^{103}$Rh($^{16}$O, 3$\alpha$3n)$^{106m}$Ag may be explained assuming that only $\alpha$-particle fuses with the target-nucleus leading to $^{107}$Ag*, which emits a neutron leaving behind the residue $^{106m}$Ag. Similarly, the reactions $^{103}$Rh($^{16}$O, 3$\alpha$3n)$^{104g}$Ag and $^{103}$Rh($^{16}$O, 3$\alpha$4n)$^{103g}$Ag, may be explained, if 3 and 4 neutrons are emitted, respectively from $^{107}$Ag*. In these cases, $^{12}$C may be assumed to be a spectator. Further, in order to understand the ICF contributions in all $\alpha$-emitting channels, an attempt has also been made to estimate ICF fraction from the comparison of experimentally measured EFs and theoretically calculated ones [48]. In the present work, the contribution of ICF has been separated out for $^{111}$In($2\alpha$2p2n), $^{110}$In($2\alpha$n), $^{108}$In($2\alpha$3n), $^{106m}$Ag($3\alpha$2n), $^{104g}$Ag($3\alpha$3n) and $^{103g}$Ag($3\alpha$4n) reaction products which are expected to have contribution from both CF and/or ICF processes. The deduced ICF cross-sections for the residues $^{111,110,108}$In and $^{103g,104g,106m}$Ag have been plotted in Fig. 6(a). From these figure, it may be observed that the ICF contribution in all $\alpha$-emitting channels increases with projectile energy, as expected.
Further, as indicated in Figs. 4(a), (b) and (d), ICF is expected to contribute significant amount to the evaporation residue cross-sections. As such, an attempt has been made to deduce the ICF contribution from experimentally measured and theoretically predicted EFs. Although, it is not possible to directly obtain the relative contribution of CF and ICF from the measurement of EFs, therefore some systematics has been followed. As already mentioned, the enhancement in the experimentally measured production cross-sections over theoretical model predictions based on CF calculations may be attributed to the contribution from ICF. As such, the ICF contribution for individual channels has been deduced by subtracting CF cross-sections ($\sigma_{\text{CF}}$) (predicted by theoretical model code) from the experimentally measured cross-sections ($\sigma_{\text{EXP}}$) at respective projectile energies, as suggested by Gomes et al. [3]. The ICF contributions ($\sigma_{\text{ICF}}$) deduced as mentioned in Ref. [3], for presently measured evaporation residues are plotted in Fig. 6(a) along with the sum of cross-section for all ICF-channels ($\sum \sigma_{\text{ICF}}$) as a function of projectile energy. The lines drawn in these figures are just to guide the eyes. As can be seen from these curves, in general, the ICF contribution increases with projectile energy. It may be because of the fact that the projectile break-up probability of incident ion in the field of the target nucleus significantly increases with incident energy.

As mentioned, the sum of cross-sections for all measured ICF-channels ($\sum \sigma_{\text{ICF}}$) and the sum of cross-sections for all CF-channels ($\sum \sigma_{\text{CF}}$) obtained from theoretical model predictions are plotted along with the total fusion cross-section ($\sigma_{\text{TF}} = \sum \sigma_{\text{CF}} + \sum \sigma_{\text{ICF}}$) in Fig. 6(b). It can be observed from this figure that the CF component has measurable contribution even at $\approx 58$ MeV, while ICF contribution seems to start from $\approx 66$ MeV, in the present work. Further, it may be noted from Fig. 6(b), that the separation between the plots for $\sum \sigma_{\text{TF}}$ and $\sigma_{\text{CF}}$ increases with projectile energy, which indicates larger contribution from ICF at relatively high projectile energies. This may be because of the fact that the break-up of projectile may be favored as the projectile energy increases. As such, in order to have better representation of projectile energy dependence on ICF contribution, the percentage ICF-fraction ($F_{\text{ICF}}$) has been estimated from the experimentally measured and theoretically calculated EFs similar to as in Ref. [48].

![Fig. 5. Experimentally measured and theoretically calculated EFs for different residues expected to be populated via only incomplete fusion ($\alpha x n/2\alpha x n$-channels) of $^{16}$O with $^{103}$Rh.](image-url)
Fig. 6. (a) Deduced EFs for different ICF ($\alpha x n/2\alpha x n$-channels) residues, and (b) total fusion probability ($\sigma_{\text{TF}}$) along with the sum of complete fusion ($\Sigma \sigma_{\text{CF}}$) and incomplete fusion ($\Sigma \sigma_{\text{ICF}}$).

$F_{\text{ICF}}$ for $^{16}\text{O} + ^{103}\text{Rh}$ system has been deduced at different energies and is plotted as a function of projectile energy normalized with Coulomb barrier ($E_{\text{beam}}/V_b$) in Fig. 7. The normalized projectile energy ($E_{\text{beam}}/V_b$) has been used to incorporate the effect of Coulomb barrier while comparing different projectile-target combinations in a plot, which is reported as best data reduction procedure for different systems [53]. As can be seen from Fig. 7, the relative percentage $F_{\text{ICF}}$ is found to be $\approx 5.5\%$ of the total fusion cross-section ($\sigma_{\text{TF}}$) at $E_{\text{beam}}/V_b = 1.4$, which increases with normalized projectile energy. However, at $\approx 83$ MeV (i.e. $E_{\text{beam}}/V_b = 1.77$) the relative percentage of $F_{\text{ICF}}$ approaches to $\approx 16\%$ of $\sigma_{\text{TF}}$. Further, in order to support these measurements, similar energy dependence of $F_{\text{ICF}}$ for $^{16}\text{O} + ^{159}\text{Tb}$ and $^{16}\text{O} + ^{169}\text{Tm}$ systems taken
from our recent publications are also shown in the inset of this figure [48]. As can be noticed from the comparison of $F_{\text{ICF}}$ for different projectile target combinations, the $F_{\text{ICF}}$ is found to be $\approx 5.5\%$, $\approx 20\%$ and $\approx 30\%$ at the same $E_{\text{beam}}/V_b(=1.4)$ value for $^{16}\text{O}+^{103}\text{Rh}$, $^{16}\text{O}+^{159}\text{Tb}$ and $^{16}\text{O}+^{169}\text{Tm}$ systems, respectively. This striking observation clearly reveals the sensitiveness of $F_{\text{ICF}}$ to the mass-asymmetry of interacting partners, which supports the systematics presented by Morgenstern et al. [15–18].

Moreover, similar mass-asymmetry dependence for ICF has been reported in one of our recent publications [48], wherein, it was emphasized that the $F_{\text{ICF}}$ depends not only on the mass-asymmetry of interacting partners but also on projectile structure, which plays an important role in the underlying reaction mechanism. In the present work for $^{16}\text{O}+^{103}\text{Rh}$ system, the similar systematics for ICF processes has been studied at given energies and presented in Fig. 8, at a constant value of $E_{\text{beam}}/V_b = 1.4$, as a representative case. As can be seen from this figure, the $F_{\text{ICF}}$ is found to increase with mass-asymmetry, individually for both $^{16}\text{O}$ and $^{12}\text{C}$ as a projectile. It may, further, be pointed out that if one considers only the mass-asymmetry of interacting partners as presented by Morgenstern et al. [15–18], the $F_{\text{ICF}}$ do not explain the observed systematics. As such, on the basis of systematics presented in this work and in our earlier publication [48], it may be inferred that not only mass-asymmetry of interacting partners but also the projectile structure effects should also be taken into account, while predicting the $F_{\text{ICF}}$. Further, the systematics can be supported and strengthened by some more experimental data for various projectile–target combinations.
5. Summary and conclusions

Measurement and analysis of EFs for several radio-nuclides produced via CF and/or ICF in $^{16}$O + $^{103}$Rh system at energies $\approx 3$–5 MeV/nucleon have been presented in this paper. Some $\alpha$xn- and $\alpha$xn-channels are found to have contribution from both direct and pre-cursor decay of higher charge isobar. As such, an attempt has been made to deduce the independent production cross-section from cumulative and pre-cursor decay contribution of different radio-nuclides. The experimentally measured EFs have been compared with PACE4 predictions after correcting the pre-cursor decay contribution (if any), which have been found to agree reasonably well for $\alpha$xn/pxn-channels (CF-products). However, in case of $\alpha$-emitting channels, significant enhancement in the production cross-sections has been observed as compared to theoretical model predictions. The observed enhancement in experimentally measured cross-sections may be assumed to come from the prompt break-up of projectile into $\alpha$-clusters ($^{16}$O $\Rightarrow$ $^{12}$C + $^{4}$He and/or $^{8}$Be + $^{8}$Be) leading to the various ICF processes. It has also been observed that the probability of break-up increases with the projectile energy, which reveals the dependence of ICF processes sensitively on projectile energy. Moreover, in order to further confirm the findings of Morgenstern et al. [15–18], and of our recent publication [48], the dependence of $F_{\text{ICF}}$ on mass-asymmetry and/or the projectile structure effect, experimental data for five experiments have been compared, wherein, the $F_{\text{ICF}}$ is found to increase with mass-asymmetry, individually for both $^{16}$O and $^{12}$C as a projectile. Therefore, it can be inferred that mass-asymmetry of interacting partners along with projectile structure effects should also be taken into consideration to explain the $F_{\text{ICF}}$ for different projectile–target combinations. As such, it may be concluded that apart from CF, the ICF is
also found to contribute significantly to the total reaction cross-section even at projectile energies as low as \(\approx 3–5\) MeV/nucleon. Therefore, while predicting the total reaction cross-section for a projectile–target combination, the contribution coming from ICF should also be taken into consideration. Further, the additional information of underlying processes can also be obtained by comparing a rich set of experimental data for various projectile–target combinations. However, the measurement of recoil range distribution and spin-distribution of residues populated by CF as well as ICF using particle-\(\gamma\) coincidence technique both at relatively low and higher bombarding energies may provide a more clear understanding of the incomplete fusion processes.

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References

I. INTRODUCTION

During the last couple of decades, efforts have been made to understand the dynamics of nuclear interaction in light and heavy particle induced reactions. In light particle induced reactions, two apparently different mechanisms such as the compound nucleus (CN) and the direct reactions appear to be dominant. In the CN mechanism, the interaction between projectile and target nucleus takes place in such a way that the excitation energy is shared statistically among all the constituent nucleons of the composite system so that memory of its formation is lost. The time scales involved in the constituent nucleons of the composite system so that the excitation energy is shared statistically among all projectile and target nucleus takes place in such a way be dominant. In the CN mechanism, the interaction between

To study the dynamics of heavy ion fusion reactions in the lower mass region, experiments were carried out to measure the cross sections of radioactive residues produced in the interaction of the $^{16}\text{O}$ ion with $^{27}\text{Al}$ target nucleus at 19 different energies in very close intervals covering the energy range from $\approx 58$ to 94 MeV, using the well-known recoil catcher off-line $\gamma$-ray spectroscopy technique. The simulation of experimental data was performed using statistical-model-based computer codes, viz., CASCADE, PACE2, and ALICE-91. The analysis of measured excitation functions indicates that these residues are likely to be produced by complete fusion, incomplete fusion, and direct reaction processes. Furthermore, to confirm the contribution of different reaction channels, a complementary experiment was performed that measured the angular distributions of the residues produced in the $^{16}\text{O}+^{27}\text{Al}$ system at 85 MeV beam energy. The analysis of the results of both experiments indicates that at these energies, the direct reactions compete with complete fusion and incomplete fusion reaction processes.

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To explain the mechanism of such reactions, several models have been proposed. At present, model-based computer codes are available that include preequilibrium emission to explain the complete features of the experimental data. It is now possible to theoretically describe the sequence of processes, which has led to the comprehensive description of a large set of cross section data for different projectile-nucleus interactions.

In recent years, with the availability of medium energy heavy ion (HI) accelerators, it has become possible to study the nuclei at higher excitation energies and angular momenta, where, along with complete fusion (CF) processes, such processes as incomplete fusion (ICF) or breakup fusion, deep-inelastic collision (DIC), quasielastic collision (QEC), direct reaction (DR), transfer reaction (TR), PE emission, etc., are also likely to occur [3]. Thus, in HI reactions, the cross section is shared predominantly among the following processes: those leading to complete fusion, deep-inelastic collision, and quasielastic collision.

As the energy increases, one observes, in addition to light particles, beam like particle also, evidently emitted at an early stage of the reaction known as ICF particles. This emission is referred to as breakup fusion or ICF. The interplay between fusion and breakup fusion processes takes place at beam energies as low as just above the Coulomb barrier [4–9]. This observation led to a renewed interest to the study of the dynamics of HI reactions. Furthermore, the different behaviors of HI interactions, which depend on the energy regime, entrance channel mass asymmetry, etc., are still some of the unanswered and important open questions.

There are several ways to classify HI interactions. One of them is in terms of the impact parameter [3]. At higher values of impact parameter, the DR may take place, leading to few nucleon transfer processes. However, at smaller impact parameter values, the CF, ICF, and DIC processes may be dominant. In complete fusion reactions, the incident ion is
completely absorbed by the target nucleus, forming an excited composite system from which particles and/or γ rays may be emitted after the formation of the equilibrated compound nucleus.

However, in the case of ICF, the projectile is assumed to break up in the vicinity of the nuclear field of the target nucleus into the fragments called projectile-like fragments (PLFs), and only one of the PLFs fuses with the target nucleus, while the remaining PLFs continue to move in the forward direction with approximately the same velocity as that of the incident ion. The ICF reactions have been reported to have the following characteristics: (1) a forward peaked angular distribution of PLFs, which are predominantly emitted at the beam velocity and are generally viewed as fast breakup of the projectile, (2) a linear momentum transfer less than that of complete fusion, resulting in a smaller range of the evaporation residues, (3) a relatively higher measured cross section than that predicted by statistical models, and (4) a higher energy of the direct α particles than that of the evaporation α particles from the equilibrated compound nucleus. Various models have been proposed to describe the dynamics of ICF reactions, but none of them is able to explain the experimental data over a large energy range and mass region as well. It may not be out of place to mention that there is no satisfactory theoretical support so far for ICF reactions that can be used to simultaneously explain complete and incomplete fusion processes.

Furthermore, DICs may also be likely at these energies, in which the mass of the resulting nuclei are close to the mass of the projectile and target nuclei. The deep-inelastic collision may be characterized by substantial dissipation of initial kinetic energy and angular momentum. The time scale at which DICs are expected to occur is less than the CN lifetime, but long enough for the exchange of a significant number of nucleons between the target and the projectile. One may get the information about the mechanism through the measurement and analysis of cross section data, recoil range, and angular distributions of the residues produced in the interaction of two heavy nuclei. The cross section data obtained for such channels have a wide range of applications. Therefore, the above study is not only an important subject in its own right, but also significant for its impact on related fields of investigation and for its rich variety of applications. In this context, a program code PACE2 [15] was used for the measurement and analysis of cross sections for the reactions in the above system employing the activation technique in the energy range 10.5–1 MeV/nucleon, using a NaI (Tl) detector to identify γ rays of interest and an end-window gas flow proportional counter to resolve β decay. The energy spread of the data points are substantially large. It may, however, be pointed out that no theoretical interpretation of the data was made [13]. Furthermore, it has been mentioned that observed trend of the data indicates a CN mechanism. However, more recently, McKenna et al. [14] tried to reproduce the experimental data [13] in an experiment using a high intensity laser produced plasma beam. They also performed theoretical calculations [14] using the Monte Carlo code PACE2 [15]. They reported that residue 34Cl is produced by the evaporation of two α particles and one neutron from the compound nucleus. Furthermore, the production of other radioisotopes, viz., 27Mg, 24Na, and 24Ne, was attributed to the compound nucleus as well as to direct reactions. It is not out of place to mention here that incomplete fusion and deep-inelastic collision are also dominant mechanisms in HI reactions at these energies, and hence the contributions of these reaction channels are also required to be taken in to account.

In the present work, the excitation functions (EFs) for radioactive residues produced in the interaction of 16O ion with 27Al have been measured in order to study the reaction dynamics, particularly in the low mass region. Most of the studies in which the occurrence of ICF was observed were carried out generally with heavier mass target nuclei. Though initial studies on incomplete fusion have been carried out at energies ≈10 MeV/nucleon using rare-earth targets [11], there are very few studies with lower mass target nuclei. One advantage of using a lighter mass system is to avoid the possibility of fission, which is one of the competing modes in HI reactions on heavier target nuclei at these energies. Furthermore, if heavier targets are used, the emission of α particles from the fused excited system is likely to be substantially reduced [12] because of the high Coulomb barrier. As a result, the emission of α particles in incomplete fusion channels may give rise to residues which may have very little contribution from complete fusion channels. Measurement and analysis of EFs [4,5] in HI reactions for heavier target nuclei have indicated that ICF is an important component of the reaction mechanism at these energies.

With the motivation to determine the contribution of incomplete fusion processes in light mass target nuclei, the measurement and analysis of the cross sections for the reaction channels (2αn), (3α3p), (3α3pn), (4α2pn), and (4α3p) produced in the 16O+27Al system have been carried out at 19 different energies at very close intervals covering the energy range from ≈58 to 94 MeV. There are mainly two experimental methods which are widely used to study the dynamics of HI reactions: (1) off-beam γ-ray spectrometry by the measurement and analysis of the excitation functions (EFs), recoil range distributions, and angular distributions of the residues produced in the projectile-target interaction using the activation technique and (2) in-beam γ-ray spectrometry by detecting the breakup α particles of the projectile, i.e., projectile-like fragments, in coincidence with the prompt γ rays of the populated residues using the particle-γ coincidence technique. The former is based on the measurement of the activity produced in radioactive residues using off-line γ-ray spectroscopy.

In the literature [13], the measurement of cross section data exists for the 16O+27Al system using the activation technique. Landenbaurer-Bellis et al. [13] measured the cross section for the reactions in the above system employing the activation technique in the energy range 10.5–1 MeV/nucleon, using a NaI (Tl) detector to identify γ rays of interest and an end-window gas flow proportional counter to resolve β decay. The energy spread of the data points are substantially large. It may, however, be pointed out that no theoretical interpretation of the data was made [13]. Furthermore, it has been mentioned that observed trend of the data indicates a CN mechanism. However, more recently, McKenna et al. [14] tried to reproduce the experimental data [13] in an experiment using a high intensity laser produced plasma beam. They also performed theoretical calculations [14] using the Monte Carlo code PACE2 [15]. They reported that residue 34Cl is produced by the evaporation of two α particles and one neutron from the compound nucleus. Furthermore, the production of other radioisotopes, viz., 27Mg, 24Na, and 24Ne, was attributed to the compound nucleus as well as to direct reactions. It is not out of place to mention here that incomplete fusion and deep-inelastic collision are also dominant mechanisms in HI reactions at these energies, and hence the contributions of these reaction channels are also required to be taken in to account.

In the present work, an attempt has been made to explain the experimentally measured cross sections using statistical-model-based computer codes, viz., CASCADE [16], PACE2 [15], and ALICE-91 [17]. To obtain complementary information about the processes involved in lighter mass symmetric systems, angular distributions of the residues produced in the 16O+27Al system have also been measured at 85 MeV beam energy. Experimental details are discussed in Sec. II of the paper; the analyses of the excitation functions and angular distributions are presented in Secs. III and IV, respectively. Conclusions are given at the end of the paper.
II. EXPERIMENTAL DETAILS

The experiments were performed at the Inter University Accelerator Centre (IUAC) formerly known as Nuclear Science Center (NSC), New Delhi, India, using the 15 UD Pelletron accelerator facility. The experiments for excitation functions and angular distribution measurements were carried out in the general-purpose scattering chamber (GPSC) of 1.5 m diameter dedicated for such studies, having an in-vacuum transfer facility. The time interval between the end of irradiation and the beginning of counting was minimized using in-vacuum transfer of samples from the scattering chamber to the counting system. Details of the measurements of excitations functions and annular distributions are given in the following subsections.

A. Excitation functions

The spectroscopically pure self-supporting foils of $^{27}$Al (purity $\approx 99.999\%$) were rolled to obtain samples of the desired thickness. Target thickness plays a crucial role in each measurement. Therefore, measurement of target thickness must be as accurate as possible to obtain accuracy in the measured cross section data. In the present case, the thicknesses of the target as well as the catcher foils were determined using the $\alpha$-transmission method. This method is based on the measurement of the energy lost by 5.485 MeV $\alpha$ particles obtained from a $^{241}$Am source while passing through the target thickness. For thickness determination, the stopping power values were calculated using the program SRIM-2006. The measured thickness of $^{27}$Al foils were $\approx 1.8$ mg/cm$^2$. The Al samples and the degrader/catcher foils were cut into $1.2 \times 1.2$ cm$^2$ squares and pasted onto rectangular target holders having concentric holes of 1.0 cm diameter. In the present work, two stacks containing five alternating samples of natural Tm and Al and another two stacks containing five and four alternating samples of natural Tb and Al, respectively, were used for the EF studies. The samples of Tm and Tb served as energy degraders and catchers. In separate communications [18,19], the activations of the Tb and Tm samples were studied for the measurement of cross sections for a large number of channels. The calculations of energy loss in the stack were done using the energy range program SRIM-2006. Four stacks containing in all 19 $^{27}$Al samples and an equal number of energy degraders were irradiated by the $^{16}$O$^+$ beam at four different energies, i.e., 86, 88, 92, and 95 MeV. The irradiation of these four stacks covered the desired energy range $\approx 58$ to 95 MeV. As the beam traverses the samples of the stack, the energy spread goes on increasing toward the last sample. As a typical example, the energy spread at $\approx 58$ MeV is $\approx 2\%$. Keeping in mind the half-lives of interest, the irradiation of each stack was carried out for $\approx 8$ h duration. The beam currents were $\approx 50$ nA. The total charge collected in the Faraday cup was used to calculate the flux of the incident beam. Furthermore, to monitor the flux of the incident beam, in an auxiliary experiment, two Rutherford monitor detectors kept at $\pm 30^\circ$ with respect to the beam direction were used. The two readings of the flux agreed with each other within an uncertainty of about 5%. It may, however, be pointed out that the unreacted beam is dumped in the Faraday cup about 1 m away from the samples.

In the present work, the analysis of the $^{16}$O+$^{27}$Al system is being presented which provides a data set of 19 points at very close energy intervals. The stacked foil activation technique followed by off-line $\gamma$-ray spectroscopy was employed to determine the cross sections for various reaction residues. In the stacked foil technique, the energetic beam traverses through all the samples with degrading beam energies; as such, it is possible to bombard different samples of the stack at different energies. The activities induced in the various samples were recorded by counting the Al samples as well as the degrader/catcher foils using a high-purity Ge $\gamma$-ray spectrometer coupled to a personal-computer-based multichannel analyzer setup employing the FREEDOM software [20]. The counts under photo peaks of interest were taken for the determination of cross section after proper background correction. The HPGe $\gamma$-ray spectrometer (resolution $\approx 2$ keV for 1.33 MeV $\gamma$ ray of $^{60}$Co) was precalibrated for both energy and efficiency employing various standard $\gamma$ sources such as $^{22}$Na, $^{54}$Mn, $^{57,60}$Co, $^{113}$Ba, $^{137}$Cs, and $^{152}$Eu. To determine the geometry-dependent efficiency $G_\gamma$ for $\gamma$ rays of different energies, a standard source of $^{152}$Eu of known strength was used. A typical plot of $G_\gamma$ at 2 cm distance from the sample to the detector system is shown in Fig. 1. Relevant portions of the observed $\gamma$-ray spectrum of the irradiated $^{27}$Al sample at 82 MeV $^{16}$O beam are shown in Fig. 2.

The peaks in the observed $\gamma$-ray spectrum were assigned to different reaction residues on the basis of their characteristic energy of $\gamma$ lines as well as measured half-lives. A typical curve used to determine the half-life of the residue $^{34m}$Cl is shown in Fig. 3. A list of reactions, energies of the identified $\gamma$ rays, and their branching ratios [21] are given in Table I.

The measured intensities of the characteristic $\gamma$ rays were used to compute the reaction cross sections using the formula [22]

$$\sigma_\gamma(E) = \frac{C_\gamma \lambda \exp(\lambda t_l)}{N_0 \phi PK(G_\gamma)[1 - \exp(-\lambda t_l)][1 - \exp(-\lambda t_o)]}, \quad (1)$$

FIG. 1. Typical plot of photo peak efficiency of HPGe detector as a function of $\gamma$-ray energies of the $^{152}$Eu source.
TABLE I. Reactions, measured half-lives, identified γ rays, and their branching ratios.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Reaction</th>
<th>Half-life</th>
<th>$E_\gamma$ (keV)</th>
<th>Branching ratio (%)</th>
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<tr>
<td>1</td>
<td>27Al(16O, 2αn)34Cl</td>
<td>32.2 min</td>
<td>146.5</td>
<td>40.5</td>
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<tr>
<td>2</td>
<td>27Al(16O, 3α3p)28Mg</td>
<td>20.9 h</td>
<td>400.5, 1342.3</td>
<td>36.0, 54</td>
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<tr>
<td>3</td>
<td>27Al(16O, 3α3pn)27Mg</td>
<td>9.4 min</td>
<td>843.7</td>
<td>73.0</td>
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<tr>
<td>4</td>
<td>27Al(16O, 4α2pn)24Na</td>
<td>14.6 h</td>
<td>1368</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>27Al(16O, 4α3p)24Ne</td>
<td>3.8 min</td>
<td>472.2</td>
<td>100</td>
</tr>
</tbody>
</table>

where $C_0$ is the observed counts under the photo peak during the accumulation time $t_a$ of the induced activity of decay constant $\lambda$, $N_0$ the number of target nuclei irradiated for time $t_i$ with a particle beam of flux $\phi$, $t_l$ the time lapse between the stop of irradiation and the start of counting, $P$ the branching ratio of the characteristic $\gamma$ ray, and $G_\varepsilon$ the geometry-dependent efficiency of the detector for the $\gamma$ ray of a given energy. Proper correction for the geometry-dependent efficiency was taken into account for each case. The factor $[1 - \exp(-\lambda t_i)]$, known as the saturation correction, takes care of the decay of evaporation residues during the irradiation. The corrections for the decay of the induced activity due to the delay between the stop of irradiation and the start of counting and during the data accumulation are taken into account via the factors $\exp(\lambda t_l)$ and $[1 - \exp(-\lambda t_i)]$, respectively. $K = [1 - \exp(-\mu x)/\mu x]$ is the correction for the self-absorption of the $\gamma$ radiation in the sample thickness itself, where $x$ is the thickness of the sample and $\mu$ is the energy-dependent $\gamma$-ray absorption coefficient.

The experimentally measured values of cross sections at different energies for the reactions 27Al(16O, 2αn)34Cl, 27Al(16O, 3α3p)28Mg, 27Al(16O, 3α3pn)27Mg, 27Al(16O, 4α2pn)24Na, and 27Al(16O, 4α3p)24Ne are given in Table II.

**B. Angular distributions**

A separate experiment has also been carried out to measure the angular distribution of recoiling residues produced in the 16O+27Al system at 85 MeV beam energy. In this experiment, an Al target supported by Tm material of thickness $\approx 0.48$ mg/cm$^2$ followed by a stack of thick annular concentric Al catcher foils was mounted in the irradiation chamber normal to the beam direction. Concentric annular aluminum catchers of thickness $\approx 0.3$ mm with diameters 0.81, 1.29, 1.95, 2.64, 3.27, 5.46, and 6.4 cm were used to trap the recoiling nuclei emitted at different angles. A typical arrangement of the target and catcher assembly used for the angular distribution measurements is shown in Fig. 4. The arrangement of annular catchers was placed 1.8 cm behind the target for collecting the residues emitted in seven different angular ranges, viz., 0°–13° (most forward cone), 13°–21°, 21°–30°, 30°–39°, 39°–45°, 45°–60°, and 60°–64°. The irradiation was carried out for about 11 h with a beam current of $\approx 7$ pnA. The activities induced in each catcher were followed off line for a couple of days. Typical $\gamma$ spectra indicating the region of interest for different annular Al catcher rings covering the angular range from 0°–13° to 45°–60° is shown in Fig. 5. For identification of the reaction residues, the similar procedure is adopted, as discussed in Sec. II A. Further,
the intensities of the characteristic $\gamma$ rays were used to compute the reaction cross sections at different angular ranges, using Eq. (1), given in Sec. II A of this paper. The efficiency of the detector was obtained for a point source. However, the annular catchers used for trapping the reaction residues had a finite area; therefore, a proper correction [23] was applied to deduce the cross sections for the residues of interest.

III. ANALYSIS

To obtain information regarding the mechanism involved in these reactions, the comparison of measured excitation functions was performed using three computer codes: CASCADE [16], PACE2 [15], and ALICE-91 [17]. Brief details of these codes along with their important parameters, etc., are discussed in the following sections.

A. Calculations with cascade

The code CASCADE [16] is based on Hauser-Feshbach theory [24] and is generally used to obtain the theoretical estimates of cross sections using the CN mechanism. It does not consider the possibility of incomplete fusion (ICF) and PE emission. The main advantage of this code is that it provides the option of scaling the default parameters (i.e., fission barrier, rigid-body momentum of inertia) to obtain cross section values in the mass region of interest. The decay probabilities are

![Image](https://example.com/image.png)

**FIG. 4.** Typical arrangement of target-catcher assembly used for the angular distribution measurements covering the annular range from 0°–13° to 45°–60°.

![Image](https://example.com/image.png)

**FIG. 5.** Typical $\gamma$-spectra Al-catcher rings covering the annular range from 0°–13° to 45°–60°.

<table>
<thead>
<tr>
<th>Lab energy (MeV)</th>
<th>$\sigma(^3\text{Cl})$ (mb)</th>
<th>$\sigma(^{28}\text{Mg})$ (mb)</th>
<th>$\sigma(^{25}\text{Mg})$ (mb)</th>
<th>$\sigma(^{22}\text{Ne})$ (mb)</th>
<th>$\sigma(^{22}\text{Na})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.0±1.3</td>
<td>9.40±1.69</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.46±0.08</td>
</tr>
<tr>
<td>58.7±1.3</td>
<td>14.57±2.62</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1±0.18</td>
</tr>
<tr>
<td>66.5±1.2</td>
<td>57.72±10.39</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.94±0.17</td>
</tr>
<tr>
<td>68.0±1.2</td>
<td>62.70±11.29</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.96±0.17</td>
</tr>
<tr>
<td>68.2±1.2</td>
<td>154.09±27.74</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.275±0.05</td>
</tr>
<tr>
<td>71.6±1.1</td>
<td>115.49±20.79</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.63±0.11</td>
</tr>
<tr>
<td>75.4±1.1</td>
<td>169.53±30.52</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0.89±0.16</td>
</tr>
<tr>
<td>76.2±1.1</td>
<td>100.98±18.18</td>
<td>0.08±0.01</td>
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<td>1.35±0.243</td>
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<td>77.1±1.0</td>
<td>126.40±22.75</td>
<td>0.09±0.01</td>
<td>–</td>
<td>–</td>
<td>1.17±0.21</td>
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<tr>
<td>78.8±1.0</td>
<td>95.32±17.16</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.2±0.22</td>
</tr>
<tr>
<td>81.8±1.0</td>
<td>81.96±14.75</td>
<td>2.48±0.44</td>
<td>–</td>
<td>–</td>
<td>2.35±0.42</td>
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<tr>
<td>82.0±0.9</td>
<td>120.91±21.76</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.37±0.25</td>
</tr>
<tr>
<td>85.5±0.6</td>
<td>84.79±15.26</td>
<td>2.21±0.4</td>
<td>–</td>
<td>0.12±0.03</td>
<td>7.88±1.41</td>
</tr>
<tr>
<td>85.9±0.9</td>
<td>140.79±28.26</td>
<td>3.11±0.5</td>
<td>–</td>
<td>0.11±0.02</td>
<td>5.15±0.9</td>
</tr>
<tr>
<td>88.2±0.6</td>
<td>15.53±2.80</td>
<td>1.53±0.26</td>
<td>0.22±0.05</td>
<td>0.36±0.09</td>
<td>1.03±0.18</td>
</tr>
<tr>
<td>88.5±0.8</td>
<td>–</td>
<td>0.42±0.05</td>
<td>0.2±0.05</td>
<td>–</td>
<td>1.58±0.28</td>
</tr>
<tr>
<td>91.4±0.6</td>
<td>5.43±0.98</td>
<td>–</td>
<td>0.08±0.02</td>
<td>0.22±0.05</td>
<td>1.15±0.20</td>
</tr>
<tr>
<td>93.4±0.8</td>
<td>8.26±1.48</td>
<td>0.4±0.08</td>
<td>0.11±0.02</td>
<td>0.12±0.05</td>
<td>1.5±0.27</td>
</tr>
<tr>
<td>94.4±0.6</td>
<td>4.74±0.85</td>
<td>0.2±0.06</td>
<td>0.1±0.03</td>
<td>0.1±0.03</td>
<td>1.33±0.24</td>
</tr>
</tbody>
</table>
determined by the level densities of the daughter nuclei and the barrier penetrabilities for the various channels. The optical model potentials of Becchetti and Greenlees [25] are used for calculating the transmission coefficients for protons and neutrons, and the optical model potential of Satchler [26] is used for $\alpha$ particles. The Fermi gas model is used for calculating the level densities for the product nuclei.

The partial cross section for the formation of the compound nucleus of spin $J$ and parity $\pi$ from a projectile and a target nucleus of spins $J_P$ and $J_T$, respectively, at center-of-mass energy $E$ is given by [27]

$$\sigma(J, \pi) = \frac{\pi \lambda^2}{4\pi^2} \frac{(2J + 1)(2J_P + 1)(2J_T + 1)}{S = (J_P - J_T)(L = J - S)} T_L(E),\quad (2)$$

where $T_L$ are the transmission coefficients, which depend on the energy and the orbital angular momentum $L$, and $S (= J_P + J_T)$ is the channel spin.

The total fusion cross section for the maximum angular momentum $L_c$ of the compound nucleus is given by

$$\sigma_{L_c} = \frac{\pi \lambda^2}{4\pi^2} \sum_{L=0}^{L_c} (2L + 1) T_L(E).\quad (3)$$

In statistical model calculations, the critical angular momentum $L_c$ for compound nucleus fusion may be sharp, or it may have some overlap from $L_c$ to higher $L$. The effective moment of inertia $I$ may be obtained from the low-lying states of the isotope using the relation

$$I = \frac{2}{5} mr^2,\quad (4)$$

where $r$ is the radius of spherical nucleus given by $r/A^{1/3}$.

The level density formula implies a yrast line,

$$E_{\text{rot}}(J) = \frac{J(J + 1)\hbar^2}{2I} + \Delta,\quad (5)$$

where $\Delta$ is the pairing energy which determines the zero point of the effective excitation energy. In this code, the level density parameter constant $K$ and the ratio of actual moment of inertia to the rigid-body moment of inertia of the excited system $F_0$ are the two important parameters which may be varied to match the experimental data. In HI induced reactions, the high angular momentum and excitation energy are expected to have considerable influence on the deexcitation cascade. Because in HI reactions, the increasing excitation energy also increases the angular momentum; therefore, the deformation of the nucleus due to the angular momentum effect may also be quite substantial. In calculations, the deformation effects may be included by using an angular momentum dependent moment of inertia, which results in the deviation of the yrast line from that calculated assuming the nucleus to be a rigid sphere. The level density parameter $a_f$ at the saddle point, which may be obtained from the relation $a_f = A/D_{AF}$, where $A$ is the mass number of the compound nucleus and $D_{AF}$ is a free parameter, may be varied to match the experimental data. It has been observed that the parameter $D_{AF}$ has considerable influence on calculated EFs in the higher energy region.

It may, however, be pointed out that a value of $K > 10$ may give rise to the anomalous effects in particle multiplicity [28]. In the present work, the calculations were performed consistently using the set of parameters which are widely accepted and were used in our recent publication [19]. Here, calculations have been performed taking a value of $K = 8$.

It may also be pointed out that the residue $^{34}\text{Cl}$ produced via the $^{27}\text{Al}(^{16}\text{O}, 2\alpha n)$ channel has metastable as well as ground states. In the present work, the metastable state of the residue $^{34m}\text{Cl}$ was observed through the 146.3 keV $\gamma$ ray of intensity 40.5%. Since the intensity of the ground state of the residue $^{34g}\text{Cl}$ is very low, the ground state of $^{34g}\text{Cl}$ could not be observed. The production cross sections of the residue $^{34m}\text{Cl}$ were converted into the total cross section of the residue $^{34}\text{Cl}$ by using the standard radioactive decay method. Since the code CASCADE gives the total production cross section of the residue, it is reasonable from a physics point of view to compare the total cross section of the residue $^{34}\text{Cl}$ with the calculations.

The experimentally measured and theoretically calculated EF for the reaction $^{27}\text{Al}(^{16}\text{O}, 2\alpha n)^{34}\text{Cl}$ is shown in Fig. 6. The measured values of the cross sections for the residue $^{34}\text{Cl}$ by Landenbaurer-Bellis et al. [13], which has some contribution from the residue $^{38}\text{Cl}$, are also shown. As can be seen from this figure, the measured values [13] of the cross sections of the residue $^{34}\text{Cl}$ have large uncertainties in the energy scale. In the present work, the energy uncertainty resulting from the finite thickness of the sample is much smaller. Furthermore, in the energy range of interest, Landenbaurer-Bellis et al. [13] have effectively three data points, whereas in the present work, the measurements were carried out giving 19 data points, indicating a precise measurement at a very close energy interval, as indicated in Fig. 6. As has already been mentioned, the code CASCADE does not take into account the possibility of incomplete fusion processes; therefore, the enhancement of measured cross sections as compared with the calculated EFs for the reaction $^{27}\text{Al}(^{16}\text{O}, 2\alpha n)^{34}\text{Cl}$ may be attributed to the ICF process.

The experimentally measured EFs for the reactions $^{27}\text{Al}(^{16}\text{O}, 3\alpha 3\pi)^{28}\text{Mg}$, $^{27}\text{Al}(^{16}\text{O}, 3\alpha 3\pi)^{27}\text{Mg}$, $^{27}\text{Al}(^{16}\text{O}, 4\alpha 2\pi)^{34}\text{Na}$, and $^{27}\text{Al}(^{16}\text{O}, 4\alpha 3\pi)^{24}\text{Ne}$ are shown in Figs. 7–10, where the solid curves guide the eye to

FIG. 6. Experimentally measured and theoretically calculated EFs. Literature values [13] are also shown.
FIG. 7. Experimentally measured EFs. Solid curve guides the eye to the experimental data by curve fitting.

FIG. 8. Experimentally measured EFs.

FIG. 10. Experimentally measured EFs. Solid curve guides the eye to the experimental data by curve fitting.

FIG. 9. Experimentally measured EFs. Literature values are also shown.

The experimental data by curve fitting. In Fig. 9, the literature values [13] of the cross sections of the residue $^{24}$Na are also shown. On the basis of the trends of these curves, Landenbaurer-Bellis et al. [13] concluded that these reactions are formed by evaporation processes referred to as the compound nucleus mechanism. Landenbaurer-Bellis et al. [13] in their study of the $^{16}$O+$^{27}$Al system did not compare the data with theoretical simulations. Since the calculated values of EFs using code CASCADE for these reactions are negligibly small, they are not shown in Figs. 7–10, thus the observed enhancement by several orders of magnitude over their negligible theoretical predictions for these channels may be attributed to the fact that these reactions are likely to be populated by some processes other than CN processes. Furthermore, to confirm whether these reactions are formed by CF or ICF processes, the angular distributions of these recoiling residues produced in the $^{16}$O+$^{27}$Al system have also been measured, as discussed in Sec. IV of the paper.

B. Calculations with PACE2

The theoretical estimate of the cross sections for the evaporation residues has also been obtained using code PACE2 [15], which is based on a statistical approach. It uses a Monte Carlo procedure to determine the decay sequence of an excited nucleus using the Hauser-Fechbach formalism. The angular momentum projections are calculated at each stage of deexcitation, which enables the determination of the angular distribution of the emitted particles. The main advantage of Monte Carlo calculations is that they provide correlations between various quantities, such as particles and $\gamma$ rays or angular distribution of particles. The evaporation cross sections of the residues are calculated using the Bass formula [29]. The code provides the ability to have an event-by-event traceback of the entire decay sequence from the CN system into any one of the exit channels. The optical model parameters for neutron, proton, and $\alpha$ emission were taken from Perey and Perey [15]. The $\gamma$-ray strength functions for $E1$, $E2$, and $M1$ transitions were taken from tables of Endt [30]. This code has been modified to take into account the excitation energy dependence of the level density parameter using the prescription of Kataria et al. [31]. In this code, the level density parameter $a = A/K$ is one of the important parameters, where
A is the mass number of the compound nucleus and $K$ is a free parameter. The value of $K$ may be varied to match the experimental data. In the present work, a value of $K = 8$ has been taken.

The theoretically calculated EFs using the code PACE2 for the reaction $^{27}$Al($^{16}$O, 2$n$)$^{34}$Cl are also shown in Fig. 6 as the dashed curve. The observed enhancement of the measured EFs as compared with the theoretical calculations again indicates that the residue $^{34}$Cl may not be produced only by the complete fusion process, but also by some other process such as incomplete fusion. The theoretical calculations for the reactions $^{27}$Al($^{16}$O, 3$p$)$^{28}$Mg, $^{27}$Al($^{16}$O, $3a3p$)$^{27}$Mg, $^{27}$Al($^{16}$O, 4$p$)$^{24}$Na, and $^{27}$Al($^{16}$O, 4$a3p$)$^{24}$Ne give cross sections which are negligibly small, and hence no comparison of the experimental data with the simulations of this code is made in Figs. 7–10. Thus, it may be concluded that the significant contribution to these reaction channels comes from processes other than complete fusion.

C. Calculations with ALICE-91

The code ALICE-91 [17], developed by M. Blann, may be used to calculate the equilibrium as well as pre-equilibrium (PE) emission cross sections in light and heavy ion induced reactions. The compound nucleus calculations in this code are performed using the Weisskopf-Ewing model [32], while the PE component is simulated using the geometry-dependent hybrid model [33]. In this code, the possibility of incomplete fusion is not taken into account. The particles that could be emitted are neutron, proton, deuteron, and $\alpha$ particles. The code can calculate the reaction cross sections for the residual nuclei up to mass 11 and 9 a.u. away from the compound nucleus. The Myers-Swiatecki/Lysekil mass formula [34] is used for calculating $Q$ values and binding energies of all the nuclei in the evaporation chain. The inverse reaction cross sections used in the code are calculated using the optical model [35] subroutines, although there is also an option of using the classical sharp cutoff model. The transmission coefficients are calculated using the parabolic model of Thomas [36] for heavy ions. Calculations for PE emission in this code are done assuming equipartition of energy among the initial excited particles and holes. The mean free path (MFP) for intranuclear transition rates may be calculated either from the optical model potential parameters of Becchetti and Greenlees [25] or from Pauli-corrected nucleon-nucleon cross sections [37,38]. In the present calculations, the optical potentials of Becchetti and Greenlees [25] were used.

Level densities of the residue in code ALICE-91 may be calculated either from the Fermi gas model or from the constant temperature form. The Fermi gas model gives [39]

$$\rho(U) = (U - \delta)^{-5/4} \exp[2\sqrt{a(U - \delta)}]$$

where $\delta$ is the pairing term and $U$ is the excitation energy of the nucleus. The level density parameter $a$ is taken as $A/K$. $A$ being the mass number of the nucleus and $K$ is an adjustable parameter. The level density $\rho(U)$ in constant temperature form is given as [40]

$$\rho(U) \propto \frac{1}{T} e^{U/T}.$$  \hspace{1cm} (7)

The differential cross section for emitting a particle with channel energy $\epsilon$ may be written as (cross section per unit energy to emit a particle of type $\nu$)

$$\frac{d\sigma}{d\epsilon_{\nu}} = \frac{\pi \lambda^2}{4\pi^2} \sum_{l=0}^{\infty} (2I + 1)T_I(2S_{\nu} + 1)$$

$$\times \sum_{l=0}^{\infty} T^l_{\nu}(\epsilon) \sum_{J=0}^{l+i} \rho(\epsilon, J)/D,$$  \hspace{1cm} (8)

where $\lambda$ is the de Broglie wavelength of the incident ion, $T_I$ the transmission coefficient of the $I$th partial wave of the incident ion, $\rho(\epsilon, J)$ the spin-dependent level density for the residual nucleus, $D$ the integral of numerator over all particles and emission energies, and $\epsilon$ the excitation energy of the compound nucleus. $S_{\nu}$ is the intrinsic spin of the particle $\nu$, and $T^l_{\nu}(\epsilon)$ is the transmission coefficient for the particle $\nu$ with kinetic energy $\epsilon$ and orbital angular momentum $l$.

In the Weisskopf-Ewing calculations, the nuclear moment of inertia is infinite; hence there is no energy tied to rotation, thus no level density cutoff at high spin. This code does not take into account the angular momentum involved in heavy ion reactions. However, the heavy ion projectile imparts large angular momentum to the composite system having a finite moment of inertia and hence greater rotational energy. Due to nuclear rotation, a nucleus with a given angular momentum $J$ cannot have energy below a minimum value $E^\text{min}_J$, that is,

$$E^\text{min}_J \approx J(J + 1)\frac{\hbar^2}{2I}.$$  \hspace{1cm} (9)

Here, $I$ is the moment of inertia of the composite nucleus.

In this code, the level density parameter $a$, the MFP multiplier COST, and initial excitation number $n_0$ are some of the important parameters. $a$ largely affects the equilibrium component, while $n_0$ and COST govern the pre-equilibrium component. $a$ is calculated from $a = A/K$. In code ALICE-91, the intermediate states of the system are characterized by the excitation energy $E$ and number $n_p$ of excited particles and $n_h$ of excited holes. Particles and holes are defined relative to the ground state of the nucleus and are called excitons. The initial configuration of the compound system defined by the exciton number $n_0 = (n_p + n_h)$ is an important parameter of PE formalism. In the present work, a value of $n_0 = 16$ with configuration $(8p + 8n + 0h)$ has been found to satisfactorily reproduce the experimental data, where $p$, $n$ and $h$ represent the number of excited protons, neutrons, and holes, respectively. The code ALICE-91 calculates two-body nuclear transition rates using Pauli-corrected free nucleon-nucleon scattering cross section data. The actual MFP inside the nucleus may be quite different from the one calculated using free nucleon-nucleon scattering data. To compensate for this difference, a parameter COST is provided in the code ALICE-91. A value of COST greater than zero means a smaller value of the actual MFP for nucleon-nucleon scattering inside the composite excited nucleus. In the present work, a value
of \( \text{COST} = 2 \) is found to reproduce the experimental data satisfactorily.

When ALICE-91 calculations with the above-mentioned parameter values were compared with their experimental counterparts, it was observed that the maxima of the measured EFs were at higher energies than those of the calculated EFs. This is to be expected, because in ALICE-91 calculations the angular momentum effects are not taken into account. In HI induced reactions, the incident particle imparts relatively larger angular momentum to the composite system. If, in the last stages of nuclear deexcitation, higher angular momentum inhibits particle emission more than it does \( \gamma \) emission, then the peak of the excitation function corresponding to the particle emission mode will be shifted to higher energies [41]. The effect is more pronounced in heavy ion reactions than in light ion reactions, since the rotational energy is much greater in HI reactions. An estimate of the possible shift due to angular momentum effects may be made from the nuclear rotational energy. For a rigid body, the rotational energy is given by \( E_{\text{rot}} \approx (m/M)E_{\text{lab}} \). Here, \( m/M \) is the ratio of the projectile and target nucleus masses and \( E_{\text{lab}} \) is the incident energy [41]. Since the angular momentum effects have not been considered in the Weisskopf-Ewing calculations of the present version of the ALICE-91 code, it is desirable to shift the calculated EFs by the amount approximately equal to \( E_{\text{rot}} \) as calculated above. In the present work, the calculated EFs have been shifted by \( E_{\text{rot}} \) on the energy scale. The experimentally measured and theoretically calculated EFs for the reaction \( ^{27}\text{Al}(^{16}\text{O}, 2\alpha n)^{34}\text{Cl} \) are shown in Fig. 6, where the dotted curve shows the theoretical calculation done using code ALICE-91. The observed enhancement of the measured EFs compared with the theoretical calculations for the reaction \( ^{27}\text{Al}(^{16}\text{O}, 2\alpha n)^{34}\text{Cl} \) done by this code indicates that the residue \( ^{34}\text{Cl} \) may not be produced by complete fusion but by some other processes such as ICF. Furthermore, the measured EFs for the reactions \( ^{27}\text{Al}(^{16}\text{O}, 3\alpha 3p)^{28}\text{Mg}, ^{27}\text{Al}(^{16}\text{O}, 3\alpha 3p)^{27}\text{Mg}, ^{27}\text{Al}(^{16}\text{O}, 4\alpha 2p)^{23}\text{Na}, \) and \(^{27}\text{Al}(^{16}\text{O}, 4\alpha 3p)^{24}\text{Ne} \) are shown in Figs. 7–10. The theoretical calculations for these reactions give cross sections that are negligibly small, similar to the codes CASCADE and PACE2, while the measured EFs for these channels have substantial cross sections. As such, it may be concluded that after including PE emission, which is one of the dominant mode of reaction mechanisms in heavy ion reactions, the experimental data could not be reproduced, indicating the presence of a reaction mechanism other than CF and PE processes.

IV. ANGULAR DISTRIBUTIONS

The analysis of EFs for the presently measured reactions, as mentioned in Secs. III A–III C, clearly indicates that these reactions have significant contributions other than those of CF and ICF processes. To confirm the reaction mechanism involved, a specially designed experimental setup was used as shown in Fig. 4. In this experiment, an Al target supported by a natural thulium material of thickness \( \approx 0.48 \text{ mg/cm}^2 \) followed by a stack of thick annular concentric Al catcher foils was used. Depending on the momentum transfer from the projectile to the composite system, the residues formed by CF and ICF processes will be trapped in the concentric annular aluminum catchers at different angles. The residues that are expected to be populated by a mechanism such as a direct reaction may be stopped within the thulium layer. The measured angular distributions for the reaction \( ^{27}\text{Al}(^{16}\text{O}, 2\alpha n)^{34}\text{Cl} \) is shown in Fig. 11. Two peaks are observed: one around \( 0^\circ \)–\( 13^\circ \) can be assigned to the residues populated by complete fusion, and the other peak in the angular range \( 45^\circ \)–\( 60^\circ \) can be assigned to the residues populated by ICF processes.

Note that out of the five reactions identified in the EF measurements, only the \( \gamma \) ray of 146.5 keV corresponding to the reaction \( ^{27}\text{Al}(^{16}\text{O}, 2\alpha n)^{34}\text{Cl} \) could be identified from its energy as well as the half-life of residue \(^{34}\text{Cl} \) in the angular distribution measurements. The residues formed by CF are likely to recoil in the forward cone, as such peaking of angular distribution around \( 0^\circ \) indicates the population of residue \(^{34}\text{Cl} \) via CF. However, the same residue \(^{34}\text{Cl} \) when populated by ICF of residue \(^{16}\text{O} \) will show peaks at much higher angles. Therefore, it may be concluded that the basic mechanism of population of \(^{34}\text{Cl} \) may be based on both CF and ICF processes. However, the EF analysis has clearly indicated that the other reactions, i.e., \( ^{27}\text{Al}(^{16}\text{O}, 3\alpha 3p)^{28}\text{Mg}, ^{27}\text{Al}(^{16}\text{O}, 3\alpha 3p)^{27}\text{Mg}, ^{27}\text{Al}(^{16}\text{O}, 4\alpha 2p)^{23}\text{Na}, \) and \( ^{27}\text{Al}(^{16}\text{O}, 4\alpha 3p)^{24}\text{Ne} \) are not likely to be populated via the CF process. The same is reflected from the angular distribution measurements, since no peak corresponding to these residues is identified in the \( \gamma \)-ray spectra of the angular distribution data. Thus, those residues are not likely to be populated via either complete or incomplete fusion processes. In direct reactions, the ejectile takes away a large fraction of the energy; hence, the residues formed may have ranges much smaller than those of residues formed by CF and/or ICF processes and may be trapped in the thulium layer.

V. CONCLUSIONS

Excitation functions for the reactions \( ^{27}\text{Al}(^{16}\text{O}, 2\alpha n)^{34}\text{Cl}, ^{27}\text{Al}(^{16}\text{O}, 3\alpha 3p)^{28}\text{Mg}, ^{27}\text{Al}(^{16}\text{O}, 3\alpha 3p)^{27}\text{Mg}, ^{27}\text{Al}(^{16}\text{O}, 4\alpha 2p)^{23}\text{Na}, \) and \( ^{27}\text{Al}(^{16}\text{O}, 4\alpha 3p)^{24}\text{Ne} \) produced in the \(^{16}\text{O}+^{27}\text{Al} \) system have been measured in the energy range
Theoretical calculations based on three different computer codes have been carried out using well-accepted parameters. The codes PACE2 and CAScadE used in the present work are based on Hauser-Feshbach theory for compound nucleus calculations; however, the code ALICE-91 is based on the Weisskopf-Ewing model for compound nucleus calculations and the geometry-dependent hybrid model for simulating preequilibrium emission. Though preequilibrium emission may have considerable influence on the measured cross sections at relatively higher energies, the ALICE-91 calculations which include preequilibrium emission are not found to reproduce the experimental data. The present analysis indicates that the residues $^{27}\text{Al}$, $^{28}\text{Mg}$, $^{24}\text{Na}$, and $^{24}\text{Ne}$ are not populated either via complete or incomplete fusion processes, because theoretical calculations based on all these codes give negligible value of cross sections for their production. At present, we have no satisfactory explanation for the observed high cross sections for these channels; however, Ladenbaurer-Bellis et al. [13] have attributed their production to a direct reaction mechanism. From the study of the angular distributions of these residues, we have concluded that in the case of complete fusion, the residues are emitted in the forward cone along the beam direction; while for incomplete fusion, the recoiling residues emerge at relatively large angles with respect to the beam direction, as expected. As such, angular distributions of residues with respect to the beam direction may also provide complementary information about the complete and incomplete fusion processes. The analysis of angular distribution data has clearly indicated the significant contribution of the ICF process in the $^{27}\text{Al}(^{16}\text{O},\alpha n)^{34}\text{Cl}$ reaction.

ACKNOWLEDGMENTS

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Energy dependence of in-complete fusion processes in $^{16}O+^{181}Ta$ system: Measurement and analysis of forward recoil range distributions at $E_{\text{lab}} \leq 7$ MeV/A.

Devendra P. Singh¹,∗, Unnati¹, Pushpendra P. Singh², Abhishek Yadav¹, Manoj Kumar Sharma³, B. P. Singh¹,4, K. S. Golda⁴, Rakesh Kumar⁴, A. K. Sinha⁵, and R. Prasad¹
¹Department of Physics, Aligarh Muslim University, Aligarh (UP)-202 002, India
²INFN-Laboratori Nazionali di Legnaro, I-35020 Legnaro, ITALY
³Department of Physics, S. V. College, Aligarh (UP)-202 001, India
⁴Inter-University Accelerator Center, Aruna Asaf Ali Marg, New Delhi -110 067, India and
⁵UGC-DAE-CSR, Bidhan Nagar, Kolkata -700 098, India

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In order to study the energy dependence of in-complete fusion processes, the recoil range distributions for the reactions; $^{181}\text{Ta}(^{16}O, xn)$, $^{181}\text{Ta}(^{16}O, pxn)$, $^{181}\text{Ta}(^{16}O, \alpha n)$, $^{181}\text{Ta}(^{16}O, \alpha 2n)$, $^{181}\text{Ta}(^{16}O, \alpha 3n)$ and $^{181}\text{Ta}(^{16}O, 2\alpha 3n)$, have been measured at ≈81, 90 & 96 MeV beam energies. The disentanglement of the complete and in-complete fusion processes have been done in terms of full and partial linear momentum transfer from the projectile to the target nucleus. The measurements have been done using recoil catcher technique. The experimentally measured forward recoil range distributions have been interpreted in terms of break-up fusion model. Detailed analysis of the data indicates that in-complete fusion processes have significant contribution at energies as low as ≈5 MeV/nucleon and their contribution is found to increase with energy.

PACS numbers: 25.70. Jj., 25.70. Gh.

I. INTRODUCTION

The study of the dynamics of heavy ion (HI) collisions involving asymmetric nuclei at energies around the Coulomb barrier (CB) has been a topic of interest in recent years. In recent experiments [1–5] heavy residues populated by complete fusion (CF) with full momentum transfer and due to in-complete fusion (ICF) with partial momentum transfer have been identified. Each of these processes leads to the characteristic velocity distribution of the reaction products. As such, the measured yield of a particular isotope as a function of velocity or rather the range of residues in a stopping medium helps to identify the origin of the observed reaction products. The in-complete momentum transfer events referred to as in-complete fusion (ICF) reactions[6, 7] can be understood on the basis of disappearance of pocket in the one-dimensional inter-nuclear potential energy as the angular momentum increases. In order to reduce the effective angular momentum of the composite nucleus (CN) and to restore a pocket in the inter-nuclear potential energy, as the entrance channel angular momentum is increased, an increasing factor of the projectile may escape and carries away some of the angular momentum. Since, a portion of the projectile is not captured by the target, there is a deficit in the linear momentum of CN, when compared with the projectile momentum. An in-complete linear momentum transfer (LMT) event may be observed directly from the measurement of the velocity/range distribution [8–10] of the residues.

The model of Siwek-Wilczynska[6, 11] assumes that the maximum angular momentum ($l_{\text{crit}}$), associated with complete LMT, is given by the disappearance of pocket in the one-dimensional inter-nuclear potential energy and does not take into account angular momentum dissipation in the entrance channel. Due to the localization of this process in $l$-space, there is a strong co-relation between the captured mass and the angular momentum/excitation energy of the heavy residue. This prediction lay at the root of the angular momentum dependence of the ICF reactions[11].

Though, the ICF reactions have been extensively studied[12–14], nevertheless, no clear picture of the reaction dynamics has followed. With a view to understand various ICF processes, a variety of dynamical models/theories, like the Break-up Fusion (BUF) model[15], Hot-Spot model[16], Promptly Emitted Particle (PEP) model[17–20], the EXCITON model[21], SUMRULE model[22] etc., have been proposed to explain ICF reaction dynamics. It may be pointed out that, though, these models predict the ICF reaction cross-section at E ≥10 MeV/nucleon, but none of these models is suitable to predict the ICF processes at energies ≈5-7 MeV/nucleon. At present, it is well recognized [1, 23–27] that the ICF reactions begin with the CF reactions at moderate energies. Some of the recent studies[28–32] showed the onset of ICF processes just above the CB. Several extensive studies [4, 23, 29–39] based on excitation function (EF) and recoil range distribution (RRD) measurements are available. However, the energy dependence of ICF reactions is still lacking. In the present work, to understand the ICF reaction dynamics and to study its energy dependence, the RRDs of the CF and ICF products in $^{16}O+^{181}Ta$ system at the beam energies

¹Electronic address: dpsingh19@gmail.com
²Electronic address: bpsinghamu@gmail.com
The spectrometer was pre-calibrated both for energy and with the CAMAC-based FREEDOM[41] software. The HPGe (100 c.c. active volume coupled activities produced in each Al-catcher foil of the stacks Al-catchers were taken out of GPSC using an ITF. The target, $^{181}$Ta could be trapped at various catcher foil thicknesses. The role of break-up processes. A detailed description of the experimental set-up etc., is already presented[40], however, for the sake of completeness a brief description of the experimental methodology is given in section II. The details of the measurement of RRDs are described in section III and finally the conclusions drawn from this study are presented in section IV.

II. EXPERIMENTAL DETAILS

The experiments have been performed, using energetic $^{16}$O$^{7+}$ ion beams delivered from the 15UD-Pelletron accelerator of the Inter-University Accelerator Center (IUAC), New Delhi, India. Although, the methodological details are somewhat similar to those already given in our earlier works[32, 40], however, for quick reference, a brief description of sample preparation, irradiations, post-irradiation analysis etc., is given here.

In the present work, the isotopically pure sample of $^{181}$Ta (abundance =100%) of thickness $\approx$150 $\mu$g/cm$^2$ has been deposited by the electro-deposition technique on Al-foils of thickness $\approx$1.1-1.5 $\mu$g/cm$^2$. The thicknesses of the samples have been determined by the $\alpha$-transmission method. The samples have been pasted on rectangular Al-holders having concentric holes of 1.0 cm diameter. The irradiations have been performed using a $^{16}$O$^{7+}$ beam in the General Purpose Scattering Chamber (GPSC) which has an invacuum transfer facility (ITF). In each irradiation, stacks of thin Al-catcher foils (with the total thickness sufficient to stop CN formed via full LMT) have been placed just after the target, so that the heavy (slow) residues populated via CF and/or ICF could be trapped at various catcher foil thicknesses. The target, $^{181}$Ta has been mounted in such a way that the Al-backing first faces the beam so that the recoiling nuclei, if any, of very short range, does not stop in the target thickness itself. The beam energies provided by accelerator, in three separate irradiations were 85, 94 & 100 MeV, so that after an energy loss of $\approx$ 3.7, 3.9 & 3.5 MeV in the target backing, the incident energies on the targets are estimated to be respectively 81.3, 90.1 & 96.5 MeV. The irradiations have been carried out for the duration of $\approx$12 h, with a beam current $\approx$7 pnA.

After irradiation, the stacks of the samples as well as Al-catchers were taken out of GPSC using an ITF. The activities produced in each Al-catcher foil of the stacks were counted separately using a high purity germanium (HPGe) spectrometer of 180 c.c. active volume coupled with the CAMAC-based FREEDOM[41] software. The spectrometer was pre-calibrated both for energy and efficiency using standard $\gamma$-sources like $^{60}$Co and $^{152}$Eu. The resolution of the $\gamma$-spectrometer was found to be $\approx$2 keV, for 1.33 MeV $\gamma$-ray of $^{60}$Co source, during the counting of the samples. A list of the radio-nuclides populated in $^{16}$O$^{+}$,$^{181}$Ta system, the energy of identified $\gamma$-rays used for the decay-curve analysis along with their branching ratios are given in our earlier work on the same system[40]. The evaporation residues (ERs) populated via CF and/or ICF are supposed to be trapped at different catcher foil thicknesses, depending on the recoil velocity and/or the degree of LMT of projectile associated with the mode of formation. The $\gamma$-ray spectra of each foil have been recorded at increasing times so that the decay curve analysis can be done to verify the half-lives and identification of the residues. The measured half-lives of the residues were found to be in good agreement with the literature values[42]. A FORTRAN program EXPSIGMA based on the standard formulation[43] has been used for the determination of the production yield of evaporation residues in different catcher foils.

In the present work, the production probabilities of $^{194}$Tl(3n), $^{195}$Tl$^{9}$($4n$), $^{192}$Tl(5n), $^{195}$Hg$^{2,m}$($p3n$), $^{192}$Hg(p4n), $^{193}$Hg$^{2,m}$($p5n$), $^{192}$Au(9n), $^{193}$Au(82n), $^{190}$Au($\alpha3n$) and $^{186}$Ir$^{g}$($2\alpha3n$) nuclides produced in the $^{16}$O$^{+}$,$^{181}$Ta system have been measured at different catcher foil thicknesses to estimate the RRDs. In general, a residue populated via a specific channel, often emits several $\gamma$-rays of different energies. The cross-section for a channel has been determined from the measured intensities of several characteristic $\gamma$-rays and the final value is taken as the weighted average of cross-sections obtained for these $\gamma$-rays[44]. The production yield of different reaction products have been deduced by normalizing the experimentally measured production cross-sections with the respective catcher foil thicknesses. In order to generate RRDs, the normalized yield of a individual reaction product has been plotted as a function of cumulative catcher foil thicknesses. The sources of uncertainty are already described in Ref.[40].

III. ANALYSIS OF FORWARD RECOIL RANGE DISTRIBUTIONS

The degree of the linear momentum transfer ($\rho_{LMT}$) from the projectile to the target nucleus is the basis of recoil velocity of the reaction products, which may be used to differentiate the CF and ICF processes. As already mentioned, $\rho_{LMT}$ is proportional to the fused mass of the projectile, i.e., maximum LMT gives rise to maximum recoil velocity to the reaction product. In the CF process, the maximum $\rho_{LMT}$ from the projectile to the target nucleus is expected. For a given entrance channel the CN has pre-determined mass, energy and linear momentum. In case of ICF, partial $\rho_{LMT}$ leads
TABLE I: Experimentally measured forward recoil ranges \( R_{p(exp)} \) deduced from RRD curves and theoretically calculated most probable mean ranges \( R_{p(thc)} \) for CF components at \( \approx 81, 90 \) & \( 96 \) MeV, using the range energy relation[45] for the reaction products produced in the interaction of \( ^{16}O \) with \( ^{181}Ta \).

<table>
<thead>
<tr>
<th>Residues</th>
<th>Energy (E)( \approx 81 ) MeV</th>
<th>Energy (E)( \approx 90 ) MeV</th>
<th>Energy (E)( \approx 96 ) MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( R_{p(exp)} ) ((\mu g/cm^2))</td>
<td>( R_{p(thc)} ) ((\mu g/cm^2))</td>
<td>( R_{p(exp)} ) ((\mu g/cm^2))</td>
</tr>
<tr>
<td>(^{191}Hg(p4n))</td>
<td>265±76</td>
<td>267</td>
<td>257±47</td>
</tr>
<tr>
<td>(^{193}Tl(4n))</td>
<td>260±77</td>
<td>267</td>
<td>254±39</td>
</tr>
<tr>
<td>(^{192}Tl(5n))</td>
<td>244±58</td>
<td>267</td>
<td>255±21</td>
</tr>
<tr>
<td>(^{193}Hg^9(p3n))</td>
<td>261±82</td>
<td>267</td>
<td>257±75</td>
</tr>
<tr>
<td>(^{193}Hg^m(p3n))</td>
<td>275±75</td>
<td>267</td>
<td>270±60</td>
</tr>
<tr>
<td>(^{192}Hg(p4n))</td>
<td>252±61</td>
<td>267</td>
<td>282±57</td>
</tr>
<tr>
<td>(^{193}Hg^g(p5n))</td>
<td>276±47</td>
<td>267</td>
<td>256±47</td>
</tr>
<tr>
<td>(^{191}Hg^m(p5n))</td>
<td>249±53</td>
<td>267</td>
<td>230±65</td>
</tr>
</tbody>
</table>

TABLE II: Experimentally measured \( R_{p(exp)} \) deduced from RRD curves and theoretically calculated \( R_{p(thc)} \) for ICF components at \( \approx 81, 90 \) & \( 96 \) MeV

<table>
<thead>
<tr>
<th>Residues</th>
<th>Energy (E)( \approx 81 ) MeV</th>
<th>Energy (E)( \approx 90 ) MeV</th>
<th>Energy (E)( \approx 96 ) MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( R_{p(exp)} ) ((\mu g/cm^2))</td>
<td>( R_{p(thc)} ) ((\mu g/cm^2))</td>
<td>( R_{p(exp)} ) ((\mu g/cm^2))</td>
</tr>
<tr>
<td>(^{192}Au^6(2n))</td>
<td>256±48</td>
<td>267</td>
<td>165±27</td>
</tr>
<tr>
<td>(^{190}Au^6(3n))</td>
<td>282±50</td>
<td>267</td>
<td>181±22</td>
</tr>
<tr>
<td>(^{186}Ir^4(2s3n))</td>
<td>258±38</td>
<td>267</td>
<td>183±13</td>
</tr>
<tr>
<td>(^{192}Au^8(2n))</td>
<td>256±37</td>
<td>287</td>
<td>168±20</td>
</tr>
<tr>
<td>(^{190}Au^8(3n))</td>
<td>282±35</td>
<td>287</td>
<td>190±25</td>
</tr>
<tr>
<td>(^{186}Ir^4(2s3n))</td>
<td>262±40</td>
<td>287</td>
<td>166±27</td>
</tr>
<tr>
<td>(^{192}Au^9(2n))</td>
<td>290±47</td>
<td>298</td>
<td>200±35</td>
</tr>
<tr>
<td>(^{190}Au^9(3n))</td>
<td>294±45</td>
<td>298</td>
<td>204±43</td>
</tr>
<tr>
<td>(^{186}Ir^5(2s3n))</td>
<td>290±50</td>
<td>298</td>
<td>213±23</td>
</tr>
</tbody>
</table>

However, as representative cases to show different \( \rho_{LMT} \) components in various CF and ICF processes the RRDs for \(^{192}Hg(p4n)\), \(^{191}Au^9(2n)\) and \(^{186}Ir^5(2s3n)\) residues have been presented in Figs. 1-3, at three different beam energies each. The size of the circles, in Figs.1-3, includes the uncertainty in the yield values. As can be seen from these figures, the measured RRDs clearly indicate the different momentum transfer components, depending on the fused mass of the projectile with the target nucleus.

In case of p4n channel (Fig.1), the measured RRDs show only a single peak, at all the three bombarding energies, indicating only single linear momentum transfer component (a characteristic of CF process) involved in the production of \(^{192}Hg\). A close observation of the range distribution of \(^{192}Hg\) (Fig. 1) reveals that FRRDs peaks at relatively higher cumulative catcher thickness as the beam energy increases. It is simply because the LMT increases with beam energy. Further, it may be pointed out that, the neutron emission from the recoiling to the formation of an in-completely fused composite system in excited state. For an in-completely fused composite system, the following quantities viz., mass, energy and momenta of CN may not have unique values. This may be because of the fluctuations in the fused mass from the projectile to the target nucleus. The experimentally measured forward recoil ranges of final reaction products in the stopping medium may give an indication of the \( \rho_{LMT} \) involved. As such, the radio-nucleides populated via a lower degree of LMT, show relatively smaller depth (momentum transfer component) in the stopping medium as compared to the entire LMT populations. For a different \( \rho_{LMT} \), the residues may have different recoil ranges in the stopping medium. Therefore, the forward recoil range distributions may be used as a probe to investigate the partial fusion of the projectile in ICF processes. The normalized yields of different reaction products have been generated for the residues viz., \(^{194}Tl\), \(^{193}Tl\), \(^{192}Tl\), \(^{193}Hg^g\), \(^{193}Hg^m\), \(^{192}Hg\), \(^{191}Hg^g\), \(^{191}Hg^m\), \(^{192}Au^9\), \(^{191}Au^9\), \(^{190}Au^9\) and \(^{186}Ir^g\) and plotted as a function of cumulative catcher thickness.
nuclei may change the energy/momentum of the recoiling nucleus, depending on their direction of emission. This may be reflected in the width (FWHM) of the experimentally measured recoil range distributions. The width may also arise due to the contribution from straggling effects.

The identified reaction products and their experimentally measured most probable FRRDs, $R_p^{(exp)}$, for all the CF residues along with the theoretically estimated (using the code SRIM[45]) mean ranges $R_p^{(the)}$, are given in Table I.

The most probable recoil ranges have been theoretically calculated, assuming that, in case of CF, the incoming ion completely fuses with the target nucleus and transfers its total linear momentum to the fused system, which recoils, in order to conserve the input linear momentum. On the basis of above description, it may be mentioned that the population of reaction products $^{192}\text{Hg}$ populated via p4n channel is associated with the entire LMT from projectile to the target nucleus, and may be represented as:

$$^{16}O + ^{181}\text{Ta} \rightarrow ^{197}\text{Tl}^* \rightarrow ^{192}\text{Hg} + p4n$$

In the similar fashion, the RRDs for the residues $^{194}\text{TI}$, $^{193}\text{TI}$, $^{192}\text{TI}$, $^{193}\text{Hg}^g$, $^{193}\text{Hg}^m$, $^{191}\text{Hg}^g$ and $^{191}\text{Hg}^m$ are found to have single peak associated with complete linear momentum transfer from projectile to the composite nucleus, indicating their production via CF process only.

Further, in case of reaction channels ($\alpha$n), ($\alpha$2n) and ($\alpha$3n) where, the residues $^{192}\text{Au}^g$, $^{191}\text{Au}^g$ and $^{190}\text{Au}^g$ are populated, each of the FRRDs are found to have two peak structure. The observed FRRDs were resolved into two peaks, with Gaussian peak fitting option of ORIGIN software, one corresponding to the complete momentum transfer events and the other corresponding to the fusion of $^{12}\text{C}$ (if $^{16}O$ breaks into $^{12}\text{C} + \alpha$; and $^{12}\text{C}$ fuses) with $^{181}\text{Ta}$. As a representative case, the FRRDs for the residues, $^{191}\text{Au}^g$ have been plotted at three different energies and are shown in Fig. 2. As can be seen from this figure, the FRRDs in this case may be resolved into two Gaussian peaks (also in case of all other $\alpha$xn channels), indicating the presence of more than one linear momentum transfer components, one associated with the fusion of $^{16}O$ and the other due to the fusion of $^{12}\text{C}$. From Fig.2, it may be observed that for the residues $^{191}\text{Au}^g$, there are two linear momentum transfer components one having mean ranges at $256\pm38$, $281\pm43$ & $294\pm45$ $\mu$g/cm$^2$ at $\approx 81$, 90 & 96 MeV beam energies (indicating fusion of $^{16}O$ and the other due to the fusion of $^{12}\text{C}$). From Fig.2, it may be observed that for the residues $^{191}\text{Au}^g$, there are two linear momentum transfer components one having mean ranges at $256\pm38$, $281\pm43$ & $294\pm45$ $\mu$g/cm$^2$ at $\approx 81$, 90 & 96 MeV beam energies (indicating fusion of $^{16}O$) and at $165\pm26$, $170\pm25$ & $204\pm30$ $\mu$g/cm$^2$ (indicating fusion of $^{12}\text{C}$) at the respective three energies. It may also be observed from the Fig. 2, that the peak value of the ranges i.e., $R_p^{(exp)}$ shifts towards higher cumulative catcher.
thickness as the beam energy increases, as expected. It can be inferred that the residues $^{191}\text{Au}$ populated through $^{181}\text{Ta}(^{16}\text{O}, 2\alpha 3n)$ channel have the contributions from both the processes viz., CF and ICF. The residues $^{191}\text{Au}$ may be populated via CF and/or ICF channels i.e., via,

(a) Complete fusion of $^{16}\text{O}$ as;

$^{16}\text{O} + ^{181}\text{Ta} \rightarrow ^{197}\text{Ti}^* \rightarrow ^{191}\text{Au}^g + \alpha + 2n$;

(b) In-complete fusion of $^{16}\text{O}$ as;

$^{16}\text{O}(^{12}\text{C} + \alpha) + ^{181}\text{Ta} \rightarrow ^{193}\text{Au}^* + \alpha$ (spectator)

$^{193}\text{Au}^* \rightarrow ^{191}\text{Au}^g + 2n$

The measured ranges for the channels $\alpha n$, $\alpha 2n$ and $\alpha 3n$ via CF and ICF processes as mentioned above are presented in Table II, and are found to agree reasonably well with those calculated using code SRIM, on the basis of break-up fusion model. In these calculations, it is assumed that no energy is lost during the break-up of the incident ion. In these reactions $\alpha$-particle essentially act as spectator during the reaction, so that linear momentum transfer of the residue is reduced to $3/4$ of the CN value. Similarly, it may also be assumed that $^{16}\text{O}$ may break into 4 $\alpha$ fragments, two $\alpha$-particles may fuse with the target nucleus and the remaining two may escape without any interaction. One such case has been observed in the present work where $^{186}\text{Ir}^g(T_{1/2} = 15.8\text{ min.})$, residues are produced via $2\alpha 3n$ channel. The measured FRRDs for residues $^{186}\text{Ir}^g$ is shown in Fig.3.

As can be seen from this figure, the FRRDs may be clearly resolved into three Gaussian peaks, indicating the presence of more than one linear momentum transfer components associated with the CF of $^{16}\text{O}$ and ICF of $^{12}\text{C}$ and $^8\text{Be}$. From this figure, it may be resolved that for the population of $^{186}\text{Ir}^g$ residues, at the energies of interest, may take place via all the three linear momentum transfer components. The peaks at ranges $258\pm 38, 262\pm 40$ & $290\pm 44$ $\mu\text{g/cm}^2$ at $\approx 81, 90$ & $96$ MeV energies, respectively, may be attributed to the fusion of $^{16}\text{O}$. The ranges at $183\pm 27, 166\pm 25$ & $213\pm 30$ $\mu\text{g/cm}^2$ (fusion of $^{12}\text{C}$) and $100\pm 15, 70\pm 10$ & $121\pm 18$ $\mu\text{g/cm}^2$ (fusion of $^8\text{Be}$) at the respective energies have also been observed. As such, it can be inferred that the residues $^{186}\text{Ir}^g$ produced through $^{181}\text{Ta}(^{16}\text{O}, 2\alpha 3n)$ reaction channel have the contribution from both the processes namely, CF as well as ICF, which may be represented as due to;

(a) Complete fusion of $^{16}\text{O}$ i.e.,

![FIG. 3: (Color online) Experimentally measured forward recoil range distributions for $^{186}\text{Ir}(2\alpha 3n)$ at projectile energies $\approx 81, 90$ & $96$ MeV.](image)

![FIG. 4: (Color online) The percentage in-complete fusion fraction ($F_{ICF}$) deduced from the analysis of forward recoil range distributions as a function of normalized projectile energy. Data shown by triangle is obtained from the analysis of EFs[40].](image)
FIG. 5: (Color online) Relative strengths of the contributions coming from CF and ICF of \(^{16}\text{O}\) with \(^{181}\text{Ta}\) at projectile energies \(\approx 81, 90 \& 96\text{ MeV}\) for the production of residues \(^{191}\text{Au}(\alpha 2n)\) \& \(^{186}\text{Ir}(2\alpha 3n)\). The lines joining data points are just to guide the eyes.

\[16\text{O} + ^{181}\text{Ta} \rightarrow ^{197}\text{Tl}^* \rightarrow ^{186}\text{Ir}^* + 2\alpha + 3n;\]

(b) In-complete fusion of \(^{16}\text{O}\) i.e.,

\[16\text{O}(^{12}\text{C} + \alpha) + ^{181}\text{Ta} \rightarrow ^{193}\text{Au}^* + \alpha + 3n \quad \text{(spectator)}\]

(c) In-complete fusion of \(^{16}\text{O}\) i.e.,

\[16\text{O}(^{8}\text{Be} + ^{8}\text{Be}) + ^{181}\text{Ta} \rightarrow ^{189}\text{Ir}^* + 2\alpha \quad \text{(spectator)}\]

\[^{189}\text{Ir}^* \rightarrow ^{186}\text{Ir} + 3n\]

In case of ICF, it is assumed that, the incident \(^{16}\text{O}\) ion breaks into fragments (e.g., \(^{12}\text{C} + \alpha\) or \(^{8}\text{Be}\) & \(^{8}\text{Be}\)), as it enters in the nuclear field of target nucleus. The fragments so produced are assumed to move with the velocity of the incident ion. One of the fragments (\(^{12}\text{C}\) or \(^{8}\text{Be}\) or \(\alpha\)) fuses with the target nucleus forming a composite system, which recoils in the forward direction to conserve the input linear momentum. It may be pointed out that the events due to fusion of single \(\alpha\)-particles have not been observed in the present work.

In order to study the energy dependence of CF (full LMT) and ICF (partial LMT) components, percentage relative contributions\(^3\) of the CF and ICF components are deduced using the relation,

\[F_{ICF} = \frac{\Sigma \sigma_{ICF}}{\Sigma \sigma_{CF} + \Sigma \sigma_{ICF}} \times 100 \quad (1)\]

where, \(\Sigma \sigma_{CF}\) and \(\Sigma \sigma_{ICF}\) are the sum of cross sections (for all the measured xn, pxn, oxn and 2oxn channels obtained from the analysis of FRRDs) of CF and ICF processes, respectively.

The relative contribution of CF and ICF in the production of a particular reaction product may be computed by fitting the experimentally measured RRDs with Gaussian peaks using the ORIGIN software. The yield curves of evaporation residues obtained from RRDs are assumed to be Gaussian in nature and may be given as;

\[Y = Y_0 + \frac{A}{\sqrt{2\pi}\omega_A^2} e^{-(R-R_p)^2/2\pi\omega_A^2} \quad (2)\]

where, \(R_p\) is the most probable mean range, \(\omega_A\) is the width parameter (FWHM) of the RRD, and \(A\) is the area under the peak.

The value of the \(\chi^2\) was minimized in the present analysis using a non-linear least-square fit routine,
keeping the width ($\omega_A$) as free parameter and most probable mean range ($R_P$) has been kept at the peak position from the RRD data. As such, only the width remains as a free parameter. Moreover, as indicated in Figs.2-3, the residues show more than one RRD component. In such cases, the experimentally measured normalized yields have been fitted using the multi-peak option in a similar way as mentioned above. It may, however, be pointed out that choosing the width of Gaussian peak as a free parameter may influence the relative contributions derived from the figures. In the present work the minimization of $\chi^2$ and selected values of FWHM for the peak in complex RRD data were found to fit the experimental data satisfactorily. In the present work an attempt has been made to disentangle the CF and ICF contributions by fitting the FRRD with Gaussian constrained at a range expected for full momentum transfer to estimate their relative contributions. The percentage ICF contributions of different fusion components have been obtained by dividing the area under the ICF peak of the corresponding fusion component by the total area associated with the experimental data employing equation (1). The values of $F_{ICF}$ deduced from ICF data are plotted as a function of normalized beam energy ($E_{beam}/CB$) in Fig.4. As can be seen from this figure that the ICF fraction increases with energy rapidly at lower energies, however, at relatively higher energies the $F_{ICF}$ seems to move towards saturation. Further, extrapolation of the curve in the lower energy region clearly indicates the onset of ICF processes even at energies very close to CB i.e., from $\approx 5\%$ above CB. It may be pointed out here that the $F_{ICF}$ given in Fig. 4, presents the lower limit of in-complete fusion contributions as several other ICF channels could not be measured due to their short half-lives, and/or low intensity $\gamma$-lines of the residues. It may not be out of place to mention that similar observations of ICF contributions increasing with energy and mass asymmetry have been obtained in several papers[9] by Morgenstern et. al. However, their work involved measuring the velocity spectra employing time of flight method in lighter systems and also at relatively higher energies $\approx 10-25$ MeV/n.

Further, to understand the variation of CF and ICF contribution with energy in the individual reaction channels, the relative percentage contribution for CF and ICF processes for $\alpha n$ and $2\alpha 3n$ are plotted as a function of laboratory beam energy as representative sets. As can be seen from Figs. 5(a & b), that as the energy increases, the CF contribution goes on decreasing. However, ICF contribution (fusion of $^{12}$C) increases with energy. Further, the contribution due to the fusion of $^8$Be, observed in case of $2\alpha 3n$ channel also increases having almost similar percentage contribution as that for $^{12}$C fusion. From Figs 5(a & b), it may be observed that the relative ICF contribution for an individual channel may be as large as $\approx 50\%$ at 96 MeV, however, the overall ICF contribution at this energy is around 7% only (Fig. 4). Moreover, as already mentioned, the RRDs for the residues $^{192,191,190}$Au$^g$ and $^{186}$Ir$^g$ also show peaks corresponding to the ICF of $^{12}$C and/or $^8$Be. The experimental ICF contributions for these residues could not be compared with theoretical values as there is no satisfactory model which can give ICF contributions. Following our previous work we relate the $R_P$($exp$) to the degree of LMT or mean evaporation residue velocity, by adopting the allowance for variation of upto $\approx 10\%$ in the FWHM of FRRDs. It may be noted that de-convolution of complex range distribution of heavy residues into various ICF components due to FWHM variation is likely to affect the relative contribution by $\leq 10\%$. Further, Fig. 6 shows the ICF contributions of different Au isotopes at three different projectile energies. It may be observed from this figure that the production of $^{190}$Au$^g$ via ICF channel is nearly same at 81, 90 & 96 MeV. However, the production probability of $^{191}$Au$^g$ is largest at 90 MeV and smallest at 96 MeV with some intermediate value at 81 MeV. Further, a comparison of production probability of $^{190,191,192}$Au$^g$ at 81, 90 and 96 MeV indicates that maximum production of $^{192}$Au$^g$ is at 90 MeV and smallest at 81 MeV. However, at 96 MeV it has some intermediate value. The present data seems to be explained on the basis of BUF model assuming that as the incident ion comes near the field of target nucleus, it may break-up into its fragments and one of the fragments may fuse with the target nucleus resulting finally into partial linear momentum transfer. The presently measured FRRD data clearly indicates that the momentum (mass) lost in case of ICF processes at the time of interaction preferentially originates from the incident beam nuclei. A more detailed particle $\gamma$-coincidence experiments for this system ($^{16}$O+$^{181}$Ta) is proposed, to have better insight in the reaction mechanism and the associated $l$-values in case of CF and ICF processes. The SUMRULE model calculation, carried out for the present system, which allow the ICF processes only for $l < l_{crit}$, underestimates the presently measured ICF cross-section data by few order of magnitude. As a typical example the experimentally measured cross-sections for ($\alpha 3n$) and ($2\alpha 3n$) channels are found to be $\approx 64.0 \pm 9.6$ mb and $5.0 \pm 0.7$ mb, however, the theoretically calculated SUMRULE values are $1.32 \times 10^{-2}$ mb and $3.02 \times 10^{-3}$ mb at 81 MeV beam energy. These discrepancies indicate the deviations from the assumptions of the model. Similar deviations have also been found by Parker et. al.[1] in their study on $^{12}$C+$^{51}$V system upto 100 MeV. The SUMRULE model assumes a sharp cut-off $l$-values for CF and ICF processes. However, the present findings indicate a diffused boundary which may penetrate close to the barrier.
IV. CONCLUSIONS

The recoil range distributions for thirteen residues; $^{194}$Tl, $^{193, 195}$Tl, $^{192}$Tl, $^{193}$Hg, $^{193}$Hg, $^{192}$Hg, $^{191}$Hg, $^{191}$Hg, $^{192}$Au, $^{191}$Au, $^{190}$Au, $^{198}$Ta and $^{188}$Ta produced in $^{16}$O+$^{181}$Ta system, at $\approx 81, 90 \& 96$ MeV beam energies have been measured. The measurement and analysis of the FRRDs of reaction products presented in this paper strongly reveal a significant contribution from the partial LMT of the projectile associated with ICF in several $\alpha$ emitting channels. Different partial LMT components are attributed to the $^{12}$C and/or $^8$Be transfer from the $^{16}$O projectile to the target nucleus. An attempt has also been made to obtain the relative contribution of CF and/or ICF components. The percentage ICF contributions are found to have an onset from $\approx 5\%$ above CB. It has been found that, in general, the residues are not only populated via CF but ICF is also found to play an important role in the production of different reaction products involving direct $\alpha$-cluster emission at these energies. However, in the case of $^{192}$Au, $^{191}$Au, $^{189}$Au and $^{187}$Ta residues, the RRD data clearly indicate that the ICF reaction mechanism is dominant at the energies of interest in the present work. The results obtained indicate that the forward recoil range distributions of the residues can be an extremely valuable information for establishing the CF and ICF yields at relatively low bombarding energies.

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[41] FREEDOM, Data acquisition and analysis system designed to support the accelerator based experiments at the Nuclear Science Centre, New Delhi, India.


