Chapter V

RESULTS AND DISCUSSION
In order to understand the reaction dynamics of heavy ion interaction at about 7 MeV/nucleon energy, several experiments have been performed by our group. Results on $^{16}$O + $^{181}$Ta, $^{16}$O + $^{103}$Rh and $^{16}$O + $^{27}$Al systems are discussed here. In the present work, excitation functions (EFs) for twenty seven reactions have been measured at energies < 7 MeV/nucleon. A list of these reactions is given below:

$^{181}$Ta(O, 3n)$^{194}$Tl, $^{181}$Ta(O, 4n)$^{193}$Tl, $^{181}$Ta(O, 5n)$^{192}$Tl,

$^{181}$Ta(O, p3n)$^{193}$Hg, $^{181}$Ta(O, p3n)$^{193}$Hg,

$^{181}$Ta(O, α2n)$^{191}$Au, $^{181}$Ta(O, α3n)$^{190}$Au, $^{103}$Rh(O, p3n)$^{115}$Te,

$^{103}$Rh(O, p3n)$^{114}$Te, $^{103}$Rh(O, p4n)$^{113}$Te, $^{103}$Rh(O, 2αn)$^{110}$In,

$^{103}$Rh(O, 2αn)$^{110}$In, $^{103}$Rh(O, 3α4n)$^{103}$Ag, $^{27}$Al(O, 2αn)$^{34}$Cl,

$^{27}$Al(O, 3α3p)$^{27}$Mg, $^{27}$Al(O, 4α2pn)$^{24}$Na and $^{27}$Al(O, 4α3p)$^{24}$Ne.

The presently measured EFs have been analyzed within the framework of theoretical model code PACE4 [1]. Further, in the complementary experiments to investigate fusion in-completeness due to fractional linear momentum transfer from the projectile to the target nucleus and to separate out the relative percentage contributions of complete fusion (CF) and/or in-complete fusion (ICF), forward recoil range distributions (FRRDs) of various radio-nuclides produced via CF and/or ICF in $^{16}$O + $^{181}$Ta system have been measured at $\approx$81, 90 & 96 MeV beam energies. A list of the reactions for which the RRDs have been measured is given below:

$^{181}$Ta(O, 3n)$^{194}$Tl, $^{181}$Ta(O, 4n)$^{193}$Tl,

$^{181}$Ta(O, p3n)$^{193}$Hg, $^{181}$Ta(O, p3n)$^{193}$Hg,

$^{181}$Ta(O, p4n)$^{192}$Hg.
Further, the angular distribution (AD) for residues populated in the system \(^{16}\text{O} + ^{27}\text{Al}\) have also been measured with a view to separate the CF and ICF components.

### Analysis of Excitation Functions

In the present work, analysis of measured EFs has been done using the code PACE4 [1]. However, in case of the system \(^{16}\text{O} + ^{27}\text{Al}\), the codes CASCADE and ALICE-91 have also been used. The code PACE4 [1] is based on statistical approach. In this code the de-excitation of the compound nucleus (CN) is followed by Monte-Carlo procedure. In code PACE4 the level density parameter (LDP) \(a\) \((a = A/K)\) is an important parameter 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. In the present work, the experimental data has been tested using different values of level density parameters. Although, it is possible to explain all the EFs for a given system with different values of LDPs for individual channels, however, from the physics point of view, it is quite unreasonable. As such, in the present work all the calculations have been performed consistently using same set of parameters for all the channels of a given system. The theoretical calculations done by adopting a given set of parameters are found to agree well with the experimentally measured EFs for CF channels.

#### 5.1 \(^{16}\text{O} + ^{181}\text{Ta}\) System

In order to study the effect of ‘K’ on the EFs, calculations have been performed for different values of ‘K’ (=8, 9 and 10). The effect of variation of K on calculated EFs is shown in the Figs. 5.1.1 (a-c) and Figs. 5.1.2 (a-c), for CF channels. As can be seen from these figures, in the present work, a value of \(K =10\) is found to give a satisfactory representation of the experimental data for these channels, in general. Obviously these channels are populated only by CF. As can be seen from Fig. 5.1.1 (a) that, the measured EF for the reaction \(^{181}\text{Ta}(^{16}\text{O}, 3n)^{194}\text{Tl}\) is qualitatively in good
Figure 5.1.1: Experimentally measured and theoretically calculated EFs for $^{194}$Tl, $^{193}$Tl and $^{192}$Tl residues populated via xn ($x = 3, 4 & 5$) channels respectively in the interaction of $^{16}$O+$^{181}$Ta. The filled symbols represent the experimental data and various curves correspond to the theoretical predictions of the code PACE4 for different values of K.
agreement with the predictions based on the theoretical model code PACE4 at energies from near the threshold to well above the peak region. However, in the tail portion of the EF, the theoretical calculation of code PACE4 underestimates the experimental data. As has already been mentioned, the code PACE4 does not take into account the pre-equilibrium (PE) emission. As such, the discrepancy in the tail part between the measured and calculated EFs for 3n-channel may be attributed to the PE emission, which is likely to be a dominant mode of reaction mechanism at relatively higher energies [2]. Blann [3, 4], in his study on the role of pre-compound decay in HI reactions has indicated that the significant contribution to the PE-emission may come from the multiple pre-compound emissions at higher energies and also from equilibration collisions, if they take place in the low density region. It has also been pointed out that in HI reactions, all partial waves do not contribute to the fusion and the assumed spherical shape for corresponding HI may not be appropriate. As such, the difference of measured cross-sections as compared to statistical model CN calculations may be attributed to the PE-emission, which in case of $^{181}$Ta($^{16}$O, 3n)$^{194}$Tl reaction is more than an order of magnitude higher at $\approx$ 100 MeV. Since, code PACE4 does not taken into account the PE-emission and since, ICF can not be considered for 3n-channel, the enhancement in the measured EF as compared to PACE4 calculations in the higher energy region may be due to PE-emission. Further, as can be seen from Figs. 5.1.1 (b & c), where EFs for $^{193}$Tl(4n) and $^{192}$Tl(5n) are compared with statistical model calculations, that the shapes of the EFs are satisfactorily reproduced for the entire energy region of interest. It is because the probability of pre-equilibrium emission in these cases is much lower on account of low excitation energy.

In the case of pxn ($x = 3, 4 \& 5$) channels, there is no likelihood of ICF and, therefore, these channels are also populated by CF only, like xn channels. The measured EFs for the residues corresponding to p3n, p4n, and p5n channels are shown in Figs. 5.1.2 (a-c). It may, be pointed out that in the present work, the population cross-sections for $^{193}$Hg(p3n) and $^{191}$Hg(p5n) residues of ground as well as meta-stable states have been measured and are shown by respective symbols alongwith the sum of ground and meta-stable state contributions. It may, however, be mentioned that the general trends and shape of the measured EFs for the CF residues populated via pxn ($x = 3, 4 \& 5$) channels are satisfactorily reproduced by PACE4 calculations. Further, as can be seen from these figures that the measured
Figure 5.1.2: Experimentally measured and theoretically calculated EFs for $^{193}\text{Hg}$, $^{192}\text{Hg}$ and $^{191}\text{Hg}$ residues populated via $\text{pxn}$ ($x=3, 4 \& 5$) channels in the interaction of $^{16}\text{O}+^{181}\text{Ta}$. The filled symbols represent the experimental data and various curves correspond to the theoretical predictions of the code PACE4 for different values of parameter $K$. 

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cross-sections are somewhat enhanced as compared to the theoretical model predictions. The enhancement in the measured cross-sections over their theoretical predictions based on code PACE4 may be explained considering some contribution to these residues coming from the decay of higher charge isobar precursor (Tl) isotopes. In the case of p3n and p4n channels, the contribution of precursor decay could not be determined because of either the in-complete decay scheme or the unknown decay characteristics of the precursor. For example, in the case of p4n channel, the cross-sections for the independent decay of precursor formed by the 5n channel are found to be higher than the cross-sections for residue $^{192}$Hg populated by the p4n channel. This may happen, if the precursor does not feed the residue $^{192}$Hg formed by the p4n channel. As such, the decay schemes of $^{192}$Hg and $^{193}$Hg need further investigation. The cross-section values shown in the respective figures for these reactions also contain precursor contribution, if any. However, in the case of the p5n channel, the precursor $^{191}$Tl, which may be produced by 6n channel, is not likely to be produced in the present experiment on account of its higher threshold ($\geq 100$ MeV).

In Fig. 5.1.3, 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 $\Sigma \sigma_{CF}^{(expt)}$ shown in Fig. 5.1.3, has been compared with $\Sigma \sigma_{CF}^{(Th)}$ obtained using the code PACE4 [1] with different values of level density parameter constant ‘K’. As can be seen from Fig. 5.1.3, the $\Sigma \sigma_{CF}^{(expt)}$ is in good agreement with theoretical $\Sigma \sigma_{CF}^{(Th)}$ 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 ($a = A/8$ MeV$^{-1}$) has also been suggested by Cavinato et al. [5] for nuclei far from the magic region. The same set of parameters has been retained and used to fit the EFs of all the $\alpha$-emitting channels as well. As has already been pointed out, ICF is not taken into consideration in the theoretical model code PACE4, hence, if there is any enhancement in the experimentally measured production cross-section as compared to PACE4 calculations, it may be attributed to the ICF processes [6, 7]. In Figs. 5.1.4(a-c), the measured cross-sections for the population of $^{193-\alpha}$Au ($x = 1, 2 & 3$) isotopes via $\alpha xn$ channels are shown alongwith the
theoretical predictions of code PACE4 using consistently the same set of parameters as used for reproducing the CF channels. Note that in the case of $\alpha xn$ channels, the residues may be formed in two ways; (i) by CF of $^{16}O$ followed by the formation of an excited CN from which evaporation of neutrons and $\alpha$-particles takes place, and/or (ii) the $^{16}O$ ion breaks into $\alpha + ^{12}C$ and $^{12}C$ fuses with the target nucleus leaving an $\alpha$-particle as spectator. In this case the excited nucleus formed by the fusion of $^{12}C$ may emit neutrons while de-exciting. As can be perceived from these figures, the experimentally measured EFs are relatively higher, by several orders of magnitude, as compared to that of theoretical predictions. Since, the code PACE4 does not take ICF processes into account, the enhancement in the experimentally measured production cross-sections may be attributed to

![Graph showing the sum of cross-sections for the $xn$ and $pxn$ channels. The effect of the variation of the level density parameter $K (=8, 9 & 10)$ on calculated $\Sigma \sigma_{CF}$ is also shown.](image)

Figure 5.1.3: The sum of cross-sections for the $xn$ and $pxn$ channels. The effect of the variation of the level density parameter $K (=8, 9 & 10)$ on calculated $\Sigma \sigma_{CF}$ is also shown.
Figure 5.1.4: Experimentally measured and theoretically calculated EFs for $^{192}\text{Au}$, $^{191}\text{Au}$ and $^{190}\text{Au}$ residues populated respectively via $\alpha xn$ (x=1, 2 & 3) channels produced in the interaction of $^{16}\text{O}+^{181}\text{Ta}$. The filled symbols represent the experimental data and various curves correspond to the theoretical predictions of the code PACE4 for different values of parameter K.
the contribution coming from ICF of $^{16}\text{O}$ with the target nucleus. As such, these residues are supposed to be populated both via CF and/or ICF processes. The production of these residues may take place via the decay of CN followed by entire projectile fusion in CF process, and/or via fusion of $^{12}\text{C}$ from $^{16}\text{O}$ projectile in ICF process leading to the formation of $^{193}\text{Au}\ ^*$, an in-completely fused composite system. In this case, it has been assumed that $^{16}\text{O}$ projectile may breakup into $^{12}\text{C}+\alpha$, and out of these a part of the projectile i.e., $^{12}\text{C}$ fuses with the target $^{181}\text{Ta}$, while remaining part moves in the forward direction with almost the same velocity as that of the projectile.

The residue $^{192}\text{Au}\ ^*$ populated via $\alpha n$ channel needs special mention. The residue $^{192}\text{Au}\ ^*$ may also be populated through the decay of $^{192}\text{Hg}$ via $\beta^+/\text{EC}$ 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 curve analysis. It is known from the successive radio-active decay that, if the daughter nucleus half-life ($T_A$) and the parent nucleus half-life ($T_B$) are nearly equal, as in the present case, such that $T_A = T_B(1 + \delta)$, where $\delta \ll 1$, then the activity ratio increases approximately linearly with time, so long as $t \ll 2\tau_B/\delta$ [8], where $\tau_B$ is the mean-life time 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 production 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 Figs. 5.1.4(a) and 5.1.5(a), the cross-sections deduced as mentioned above for the independent production of $^{192}\text{Au}\ ^*$ have been plotted. Here [Fig. 5.1.5 (a)], the sum of cross-sections for all measured $\alpha n$ channels, i.e., $\Sigma\sigma_{\alpha n}(\text{expt})$, is also shown alongwith measured $\alpha n$ channels, 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 $\Sigma\sigma_{\alpha n}(\text{expt})$ has been compared with the corresponding values calculated using the theoretical model code PACE4.
Figure 5.1.5: (a) Measured EFs for $\alpha x n$ ($x = 1, 2 & 3$) channels and $\Sigma \sigma_{\alpha x n}$, (b) sum of the $\alpha x n$ channels, measured as well as calculated using PACE4 for $K (= 8, 9 & 10)$ and (c) sum of $\sigma_{ICF}$ (all $\alpha x n$) channels. In panels (a), (b) & (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.
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 PACE4 have predictions based on the CF model only. In Fig. 5.1.5 (b), a comparison of $\Sigma \sigma_{\alpha n}$(expt) has been made with $\Sigma \sigma_{\alpha n}$(Th) calculated using the CF model for three different values of physically acceptable [9] level density parameters ($K = 8, 9 & 10$). As can be seen from this figure, the $\Sigma \sigma_{\alpha n}$(Th), with any of the reasonable parameters could not reproduce $\Sigma \sigma_{\alpha n}$(expt) above 85 MeV. The measured $\Sigma \sigma_{\alpha n}$(expt) agree very well with $\Sigma \sigma_{\alpha n}$(Th) at 80 MeV. However, above this data point all the measured cross-sections are found to be much higher as compared to the theoretical predictions based on the PACE4 model. The difference between the experimental and the theoretical values of $\Sigma \sigma_{\alpha n}$ may be assigned to the ICF processes and has been denoted by $\Sigma \sigma_{ICF}$(expt). Further, the difference between $\Sigma \sigma_{\alpha n}$(expt) and $\Sigma \sigma_{\alpha n}$(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. In Fig. 5.1.5 (c), the $\Sigma \sigma_{ICF}$ values obtained by subtracting $\Sigma \sigma_{ICF}$(Th) ($K = 10$) from measured $\Sigma \sigma_{\alpha n}$ have been plotted as a function of beam energy. As can be seen from this figure, ICF production increases very rapidly with energy. In the inset of Fig. 5.1.5 (c), $\sigma_{TF}$ (total sum of cross-sections for all measured channels) and $\Sigma \sigma_{CF}$ are compared. As can be seen from this figure (inset), with the increase in energy the difference between $\sigma_{TF}$ and $\Sigma \sigma_{CF}$ continues to increase, indicating the dominance of ICF at relatively higher energies.

At energies above the CB, where $E >> V_0$, the classical formula of Weisskopf [10] for capture of charge particle by a nucleus is given by:

$$\sigma_{CF}(E) = \pi r_0^2 \left( 1 - \frac{V_0}{E} \right) \tag{1}$$

where, $V_0$ is the value of CB and $E$ is the energy in center of mass system. As such, if $\sigma_{CF}$(expt) is plotted against $1/E_{c.m.}$, it should be a linear curve. The deduced $\Sigma \sigma_{CF}$ values from $\Sigma \sigma_{\alpha n} + \Sigma \sigma_{p\alpha n} + \Sigma \sigma_{\alpha n}$(Th) have been plotted as a function of $1/E_{c.m.}$ in Fig. 5.1.6. A fit to the $\Sigma \sigma_{CF}$ 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 sub-barrier fusion.
5.2 $^{16}$O +$^{103}$Rh System

In the present work, EFs for the reactions produced in $^{16}$O+$^{103}$Rh system have also been analyzed employing the theoretical model code PACE4. Since, in these calculations "K" is an important parameter, effect of variation of $K$ (=8, 9 & 10) have been tested and are shown in Figs. 5.2.1-5.2.2, along with the experimentally measured cross-sections for the reactions $^{103}$Rh($^{16}$O, p3n), $^{103}$Rh($^{16}$O, p4n), $^{103}$Rh($^{16}$O, 2αn), $^{103}$Rh($^{16}$O, 2α3n) and $^{103}$Rh($^{16}$O, 3α4n). In the present work a value of $K$ =8 is found to give a satisfactory reproduction of experimental data for CF channels. The calculations with same value of $K$ (=8) have been found to give a satisfactory reproduction of experimental data in case of $^{16}$O+$^{181}$Ta system as well. As mentioned earlier also, it might be possible to reproduce 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 $K$ > 10 may give rise to the anomalous effect in the particle

Figure 5.1.6: Experimentally measured production cross-sections found to reproduce the Coulomb barrier of $^{16}$O+$^{181}$Ta system.
Figure 5.2.1: Experimentally measured and theoretically calculated EFs for (a) $^{115}$Te and (b) $^{114}$Te residues, populated via p3n and p4n channels in $^{16}$O + $^{103}$Rh system. The filled symbols represent the experimental data and various curves correspond to the theoretical predictions of the code PACE4 for different values of parameter K.
multiplicity [5].

As has already been mentioned, in some cases the same residue 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 ($\sigma_{\text{cum}}$) is the sum of two cross-sections due to different decay modes. The independent production cross-section ($\sigma_{\text{ind}}$) has been separated out from the cumulative cross-sections ($\sigma_{\text{cum}}$) using standard successive radio-active decay analysis [5] as discussed in section 4.1.2, in Chapter IV. Experimentally measured cross-sections for the ground and meta-stable state population of residue $^{115}\text{Te}$ are shown in Fig. 5.2.1(a). Both the measured cumulative cross-sections as well independent cross-sections deduced as discussed above are shown for both $^{115}\text{Te}^g$ as well as $^{115}\text{Te}^m$ residues, alongwith the literature values. As can be seen from this figure, there is a reasonable agreement between theoretical and experimental EFs after subtracting the contribution of precursor decay. Further, the experimentally measured EF for radio-nuclide $^{114}\text{Te}$ populated via p4n channel is also satisfactorily reproduced by theoretical model calculations within the experimental uncertainties as shown in Fig. 5.2.1 (b). Both of these radio-nuclides are populated via CF process only (as there is no $\alpha$-particle in exit-channels). The fact that the measured EFs for almost all the channels (predominantly populated by CF) 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 been used to fit the EFs for all the $\alpha$-emitting channels as well, measured in the present work.

It may be observed from Figs. 5.2.2 (a-b), the experimentally measured EFs for 2$\alpha$n and 2$\alpha$3n channels are relatively higher as compared to the theoretical predictions of code PACE4. 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 $^{16}\text{O}$ with the target nucleus. As such, these residues are expected to be populated both via CF and/or ICF of the projectile. The production of these residues may, therefore, take place (i) by the CF of $^{16}\text{O}$ with the target nucleus $^{103}\text{Rh}$ giving rise to the compound nucleus $^{119}\text{I}^*$ which then decays by emitting 2$\alpha$ particles and three neutrons,
Figure 5.2.2: Experimentally measured and theoretically calculated EFs for different residues (a) populated via $2\alpha n$, (b) $2\alpha 3n$ and (c) $3\alpha 4n$ channels in $^{16}O + ^{103}Rh$ system. The symbols represent the experimental data and various curves correspond to the theoretical predictions of the code PACE4 for different values of parameter $K$. 
and/or (ii) through the ICF of $^{16}$O (only $^8$Be fuses) forming the compound nucleus $^{111}\text{In}^*$ which emits three neutrons. In this case (ii) it has been assumed that $^{16}$O projectile breaks-up into its clusters, viz., $^8$Be + $^8$Be, a part of projectile fuses with $^{103}$Rh, while remnant moves in forward cone with a velocity almost that of projectile velocity. Further, the experimentally measured EF for $^{103}\text{Ag}^*(3\alpha4n)$ channel is shown in Fig. 5.2.2 (c). The theoretical calculations with code PACE4 give negligible cross-sections for this residue and hence are not shown in Fig. 5.2.2 (c), meaning thereby, this residue is likely to be populated predominantly via ICF. It may also be pointed out that no choice of physically reasonable parameters in theoretical calculations could reproduce the measured EF for this residue. Similarly, the theoretical calculations for $3\alpha n$ and $3\alpha 3n$ channels were also found to have negligible values [6].

It may be observed from Figs. 5.2.2(a-c), ICF is expected to contribute a 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 the enhancement in the experimentally measured production cross-sections over theoretical model predictions based on CF calculations has been 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 ($\sigma_{\text{expt}}$) at respective projectile energies. The ICF contributions ($\sigma_{\text{ICF}}$) deduced for presently measured evaporation residues are plotted in Fig. 5.2.3(a) along with the sum of cross-section for all ICF channels ($\Sigma\sigma_{\text{ICF}}$) [6], as a function of projectile energy. It may be noted that $\Sigma\sigma_{\text{ICF}}$ contains cross-sections for all measured ICF channels as indicated in Ref. [6]. 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 the break-up probability of incident ion in the field of the target nucleus increases significantly with incident energy. As mentioned, the sum of cross-sections for all measured ICF-channels ($\Sigma\sigma_{\text{ICF}}$) [6] and the sum of cross-sections for all CF-channels ($\Sigma\sigma_{\text{CF}}$) [6] obtained from theoretical model predictions are plotted along with the total fusion cross-section ($\sigma_{\text{TF}} = \Sigma\sigma_{\text{CF}}$).
Figure 5.2.3: (a) Deduced EFs for residues populated via $2\alpha n$, $2\alpha 3n$ and $3\alpha 4n$ channels. $\Sigma \sigma_{\text{ICF}}$ values have also been plotted for all ICF channels measured as given in Ref. [6]. (b) Total fusion probability ($\sigma_{\text{TF}}$) along with the sum of complete fusion ($\Sigma \sigma_{\text{CF}}$) and in-complete fusion ($\Sigma \sigma_{\text{ICF}}$).
Figure 5.2.4: Deduced percentage ICF fraction ($F_{ICF}$) as a function of normalized projectile energy for the $^{16}\text{O}+^{181}\text{Ta}$ and $^{16}\text{O}+^{103}\text{Rh}$ systems and $F_{ICF}$ values for some systems available in literature. The spline-like lines joining the experimental data points are just to guide the eyes.

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 case. Further, it may be noted from Fig. 5.2.3(b), that the separation between the plots for $\sigma_{TF}$ and $\sigma_{CF}$ increases with projectile energy, which indicates larger contribution from ICF at relatively high projectile energies.

In the present work a significant ICF contribution in almost all the $\alpha$-emitting channels have been observed. The relative contribution of CF and
ICF cross-sections is expected to depend on the energy of the projectile. As such, to study the dependence of ICF contribution on energy, for the presently studied systems, the percentage fraction of ICF cross-section ($F_{ICF}$) has been plotted in Fig. 5.2.4, as a function of beam energy normalized to CB, along with several other literature values [6, 11, 12, 13, 14].

![Graph showing the percentage ICF fraction as a function of mass asymmetry at a constant normalized projectile energy. The arrow indicates that the present value of $F_{ICF}$ for $^{16}O+^{181}Ta$ is expected to go up, if all other remaining $\alpha$-emission channels are also included.](image)

**Figure 5.2.5:** The percentage ICF fraction as a function of mass asymmetry at a constant normalized projectile energy. The arrow indicates that the present value of $F_{ICF}$ for $^{16}O+^{181}Ta$ is expected to go up, if all other remaining $\alpha$-emission channels are also included.

As can be seen from this figure, percentage $F_{ICF}$ increases with the increase in normalized beam energy for all the systems, indicating the dominance of ICF processes on relatively higher energies. To study the dependence of $F_{ICF}$ on mass asymmetry, the percent $F_{ICF}$ has been plotted in Fig. 5.2.5, 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 $^{16}$O+$^{181}$Ta system is not following the expected trend shown for other systems involving $^{16}$O beam. The present F_{ICF} value for $^{16}$O + $^{181}$Ta is found to be significantly small and is expected to go up. It may be because of the fact that in the present measurements several other $\alpha$-emission channels, e.g., 2$\alpha$x$n$ and 3$\alpha$x$n$ 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 particle $\gamma$-coincidence technique, so that the present data may be supplemented. Further, as can be seen from Fig. 5.2.4, the value of F_{ICF} is found to be $\approx 4\%$ for $^{16}$O + $^{103}$Rh system, $\approx 19\%$ for $^{16}$O + $^{159}$Tb while for $^{16}$O+$^{169}$Tm system it is found to be around $\approx 32\%$ at the same normalized projectile energy (i.e. $E_{\text{beam}}/V_{b} =1.38$). This striking observation clearly reveals the sensitiveness of F_{ICF} on the target mass. As can be seen from Fig. 5.2.5, the systematics presented [15] do not explain the experimental data as a whole. The value of F_{ICF} is found to increase with the mass asymmetry, individually for $^{16}$O and $^{12}$C projectiles. Therefore, it can be inferred that, not only mass asymmetry of interacting partners but also the projectile structure effect needs to be taken into account. The analysis of the data for $^{12}$C + $^{181}$Ta and $^{13}$C + $^{181}$Ta presented [14] also indicates that the ICF depends on the projectile structure in the beam energy range $\approx 5-6$ MeV/nucleon. The lower value of binding energy in case of $^{12}$C as compared to that in $^{13}$C results in higher break-up probability of $^{12}$C into $^8$Be+$\alpha$, near the field of the target nucleus resulting into higher ICF cross-sections. The above description indicates that the break-up fusion model of ICF appears to be somewhat more appropriate for explaining the observations of the present work.

5.3 $^{16}$O +$^{27}$Al System

The experimentally measured EFs for the reactions $^{27}$Al($^{16}$O,2$\alpha$n)$^{34}$Cl, $^{27}$Al($^{16}$O,3$\alpha$3p)$^{28}$Mg, $^{27}$Al($^{16}$O,3$\alpha$3pn)$^{27}$Mg, $^{27}$Al($^{16}$O,4$\alpha$2pn)$^{24}$Na and $^{27}$Al($^{16}$O,4$\alpha$3p)$^{24}$Ne are shown in Figs. 5.3.1(a-c) and Figs. 5.3.2(a-b). In the (a) panel of Fig. 5.3.1, the experimentally measured and theoretically calculated EFs for the production of $^{34}$Cl residues are shown. In Figs. 5.3.1(b) and 5.3.2(b) the solid lines are drawn just to guide the eyes to the experimental data. In Figs. 5.3.1(a) and 5.3.2(a), the literature [16] values
of the cross-sections are also shown. Earlier measurements on $^{16}$O+$^{27}$Al system were done [16] employing activation technique using low resolution NaI(Tl) detector and gas flow end-window $\beta$-counter. The energy spread of the data points in these measurements is substantially large [16], because of relatively large thickness of the Al-foils used. It may, however, be pointed out that no theoretical interpretation of data was made [16]. More recently, McKenna et. al., [17] tried to reproduce the experimental data [16] using a high intensity LASER produced plasma beam. They also performed theoretical calculations [17] using the Monte Carlo code PACE4. Since, in the present work, theoretical calculations for these reactions give considerably small values of cross-sections and hence are not shown in Figs. 5.3.1(b & c) and Fig. 5.3.2. As such, the observed enhancement by several orders of magnitude over their negligible theoretical predictions for these channels may be attributed to the fact that these residues are populated by some processes other than CF process. McKenna et. al., [17] reported that the residue $^{34}$Cl is produced by the evaporation of two $\alpha$-particles and one neutron from the compound nucleus formed by $^{16}$O+$^{27}$Al system. Furthermore, the production of other radio-isotopes viz., $^{27}$Mg, $^{24}$Na and $^{24}$Ne, was attributed to the compound nucleus as well as to direct reactions. It is not out of place to mention here that in-complete fusion and deep inelastic collisions are also dominant mechanisms in HI reactions at these energies, and hence the contribution of these reaction channels are also required to be taken into account. Furthermore, to confirm whether these reactions are formed by CF and/or ICF processes and to obtain the complementary information about the processes involved in lighter mass system, the angular distributions of the residues produced in $^{16}$O+$^{27}$Al system have also been measured at 85 MeV beam energy and are discussed in section 5.6 of the thesis.
Figure 5.3.1: Experimentally measured EFs for (a) the production of $^{34}$Cl, (b) $^{28}$Mg and (c) $^{27}$Mg in the system $^{16}$O+$^{27}$Al. The dark symbols represent the experimental data and in panel (a) various curves correspond to the theoretical predictions of the code PACE4. In (b) the line drawn is just to guide the eyes to the data points.
Figure 5.3.2: Experimentally measured EFs for residues (a) $^{24}$Na and (b) $^{24}$Ne. Dark circles represent the experimental data. The line drawn in panel (b) is just to guide the eyes to the data points.
5.4 FORWARD RECOIL RANGE DISTRIBUTIONS

\(^{16}\text{O}+^{181}\text{Ta System}\)

The degree of the linear momentum transfer (\(\rho_{\text{LMT}}\)) from the projectile to the target nucleus decides the recoil velocity of the reaction products. This may be used to differentiate the CF and ICF processes. As already mentioned, \(\rho_{\text{LMT}}\) 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 \(\rho_{\text{LMT}}\) from the projectile to the target nucleus is expected. For a given entrance channel the CN has predetermined mass, energy and linear momentum. In case of ICF, partial \(\rho_{\text{LMT}}\) leads to the formation of an in-completely fused composite system in the excited state. For an in-completely fused composite system, the 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 \(\rho_{\text{LMT}}\) involved. As such, the radio-nuclides populated via lower degree of LMT, will show relatively smaller depth (momentum transfer component) in the stopping medium as compared to the entire LMT populations. Therefore, the forward recoil range distributions may be used as a probe to investigate the partial fusion of the projectile in the ICF processes.

In the present work, the production probabilities of \(^{194}\text{Tl}(3n), \:^{193}\text{Tl}(4n),\)
\(^{192}\text{Tl}(5n), \:^{193}\text{Hg}^\text{m}(p3n), \:^{193}\text{Hg}^\text{m}(p3n), \:^{192}\text{Hg}(p4n), \:^{191}\text{Hg}^\text{m}(p5n), \:^{191}\text{Hg}^\text{m}(p5n),\)
\(^{192}\text{Au}^\text{m}(\alpha n), \:^{191}\text{Au}^\text{m}(\alpha 2n), \:^{190}\text{Au}^\text{m}(\alpha 3n)\) and \(^{186}\text{Ir}^{\alpha 3n}\) nuclides produced in the \(^{16}\text{O}+^{181}\text{Ta System}\) have been measured at different catcher foil thicknesses to obtain the FRRDs. The FRRDs for these residues have been measured at \(\approx 81, 90\) and \(96\) MeV beam energies. The details of the measurements of these FRRDs have already been presented in section 4.2, of Chapter IV. The production yields 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 yields of a individual reaction product have been plotted as a function of cumulative catcher foil thickness. For the better description of the FRRDs, the measured yields of each residue have
been presented (Figs. 5.4.1-5.4.12) at three different projectile energies in a single figure at three different panels.

In heavy ion reactions, it is difficult to exactly measure the degree of LMT from the projectile to the target nucleus. It is because of the recoil velocity distribution of evaporation residues due to straggling effects. In addition to this, the effects due to particle(s) emission may also contribute extra broadening in the recoil range distributions (RRDs). As such, in order to get a reliable form for the degree of LMT from the experimental data, a careful de-convolution is required. The relative contributions and precise form of RRDs in case of CF and ICF processes in the production of particular reaction products may be obtained by fitting the experimentally measured RRD data with Gaussian peaks using the ORIGIN software. The yield curves of evaporation residues obtained from RRDs assumed to be Gaussian, may be given as [18]:

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

(5.1)

where, \( R_p \) is most probable mean range, \( \omega_A \) is the width parameter (FWHM) of the RRD, and \( 'A' \) is the area under the peak. Further, the normalized yield \( 'Y' \) may be estimated by chi-square (\( \chi^2 \)) fit, from the experimentally determined production yield at different catcher-foil thicknesses. The value of \( \chi^2 \) was minimized in this analysis using a non-linear least square fit routine. As indicated in the Figs. 5.4.9–5.4.12, most of the residues show more than one LMT components. In such cases, the experimentally measured normalized yields have been fitted by assuming multi-peaks in the similar way as mentioned above.

**xn-Channels**

The measured FRRDs for the residues populated via \( xn(x = 3, 4 \& 5) \) channels at three different projectile energies \( \approx 81, 90 \) and \( 96 \text{ MeV} \) are shown in Figs. 5.4.1(a-c) to 5.4.3(a-c). As can be seen from these figures, there is only a single peak in RRDs, indicating only single LMT component involved in the production of these reaction products. As such, it may be concluded that these reactions are populated by CF processes only. 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.

As has already been mentioned, these residues viz., $^{194}\text{Tl}$, $^{193}\text{I}$, $^{192}\text{Tl}$, produced from the reactions $^{181}\text{Ta}(^{16}\text{O},3n)$, $^{181}\text{Ta}(^{16}\text{O},4n)$ and $^{181}\text{Ta}(^{16}\text{O},5n)$ respectively, are populated via CF processes. The experimental data for the FRRDs at three different energies $\approx 81$, 90 and 96 MeV can be well fitted by Gaussian distributions. In case of the residue $^{194}\text{Tl}(3n)$, the peaks are found at the cumulative thickness $\approx 265\pm 76$, $275\pm 47$ and $286\pm 48$ $\mu\text{g/cm}^2$ respectively, for incident energies $\approx 81$, 90 and 96 MeV [Figs. 5.4.1.(a, b & c)]. In case of the residue $^{193}\text{I}(4n)$, the peaks are at the cumulative thickness $\approx 260\pm 77$, $254\pm 39$ and $286\pm 67$ $\mu\text{g/cm}^2$, respectively [Figs. 5.4.2.(a, b & (c)], while for the residue $^{192}\text{Tl}(5n)$, the peaks are at the cumulative thickness $\approx 244\pm 58$, $255\pm 21$ and $264\pm 75$ $\mu\text{g/cm}^2$, respectively [Figs. 5.4.3.(a, b & c)]. The recoil ranges for the above mentioned residues have also been calculated theoretically using stopping power tables of Northcliffe and Schilling [19]. The calculated values of ranges $R_p(\text{Th})$ agree well with the measured $R_p(\text{expt})$ data and are presented in Table 5.1. It may, therefore, be taken as a conclusive evidence that these residues are produced only by the CF process. On the basis of above description, it may be mentioned that the reaction products $^{194,193,192}\text{Tl}$ populated via $xn(x=3,4\&5)$ channels are associated with the entire LMT.

pxn-Channels

In case of pxn channels, there is no likelihood of ICF therefore, these residues are also populated by CF like xn channels. The Gaussian fits of the RRD data for the residues $^{193}\text{Hg}^g$ and $^{193}\text{Hg}^m$ (populated through the reaction $^{181}\text{Ta}(^{16}\text{O}, p3n)$) at three different projectile energies $\approx 81$, 90 & 96 MeV are shown respectively in Figs. 5.4.4(a-c) and Figs. 5.4.5(a-c). As can be seen from these figures, the experimental RRD data, at three different incident energies may be fitted by a single peak, at the cumulative thickness $\approx 261\pm 82$, $257\pm 75$ and $290\pm 52$ $\mu\text{g/cm}^2$ for the residue $^{193}\text{Hg}^g$ and at $\approx 275\pm 75$, $270\pm 60$ and $292\pm 51$ $\mu\text{g/cm}^2$ for the residue $^{193}\text{Hg}^m$ respectively. The residue $^{192}\text{Hg}$ may also be populated by CF through the reaction $^{181}\text{Ta}(^{16}\text{O}, p4n)$. The Gaussian fits of the RRD data for $^{192}\text{Hg}$ at three different energies are shown in Figs. 5.4.6(a-c). It may be observed from the figures, that the experimental RRD peaks are found at the cumulative
Figure 5.4.1: Experimentally measured forward recoil range distributions for $^{194}\text{Tl}(3n)$ at projectile energies $\approx$ 81, 90 and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
Figure 5.4.2: Experimentally measured forward recoil range distributions for $^{193}$Tl$(4n)$ at projectile energies ≈81, 90 and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
Figure 5.4.3: Experimentally measured forward recoil range distributions for $^{192}\text{Ti}(5n)$ at projectile energies ≈81, 90 and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
thicknesses \( \approx 252 \pm 61, 282 \pm 57 \) and \( 291 \pm 80 \) \( \mu g/cm^2 \) respectively at three energies. While, in case of the residues \(^{191}\text{Hg}^{m}\), the measured RRD data at \( \approx 81, 90 \) & 96 MeV incident energies may be fitted by a single peak, at \( \approx 276 \pm 47, 256 \pm 47 \) and \( 277 \pm 50 \) \( \mu g/cm^2 \) and at \( \approx 249 \pm 53, 230 \pm 65 \) and \( 287 \pm 68 \) \( \mu g/cm^2 \) cumulative thicknesses, respectively as shown in Figs. 5.4.7 (a-c) & 5.4.8 (a-c). The origin of these peaks may be well understood, if it is assumed that the residue is produced by CF process in the reaction \(^{181}\text{Ta}(^{16}\text{O}, p5n)\). Since, only one peak appears at each incident energy for all the above mentioned residues, it may be concluded that these residues are populated only by CF process. Experimentally measured \( R_p(\text{expt}) \) and theoretically calculated \( R_p(\text{Th}) \) for various CF residues are given in Table 5.1. In general, the experimental values of the absorber thickness at peak position agree well with the calculations done using stopping power values within the quoted uncertainties.

\( \alpha xn \) and \( 2\alpha xn\)-Channels

The experimentally measured FRRDs for the residues \(^{192,191,190}\text{Au}^8\) and \(^{186}\text{Ir}^8\) populated via CF and/or ICF in \(^{16}\text{O}+^{181}\text{Ta}\) system at three different energies \( \approx 81, 90 \) & 96 MeV are shown in Figs. 5.4.9(a-c) to Figs. 5.4.12(a-c). As can be seen from the Figs. 5.4.9(a-c) to Figs. 5.4.11(a-c), for the residues \(^{192,191,190}\text{Au}^8\), the FRRDs in each case may be resolved into two Gaussian peaks (in case of \( \alpha xn \) channels), indicating the presence of more than one linear momentum transfer components associated with the fusion of \(^{16}\text{O} \) and/or \(^{12}\text{C} \). In case of CF, the composite system \(^{197}\text{Tl}\) is formed, which may decay by the statistical emission of an \( \alpha \)-particle and 1, 2 and 3 neutrons, respectively leaving behind \(^{192,191,190}\text{Au}^8\) residues. The above residues may also be populated, if it is assumed that, the incident \(^{16}\text{O} \) ion breaks-up into fragments (e.g., \(^{12}\text{C} \) & \( \alpha \)), as it enters in the nuclear field of the target nucleus. One of the fragments \(^{12}\text{C} \), fuses with the target nucleus forming an in-completely fused composite system \(^{193}\text{Au}^8\), which recoils in the forward direction to conserve the input linear momentum and decay by the emission of respectively one neutron forming \(^{192}\text{Au}^8\), two neutrons forming \(^{191}\text{Au}^8\) and three neutrons forming the residue \(^{190}\text{Au}^8\). As can be observed from Figs. 5.4.9(a-c), that the RRD for the residue \(^{192}\text{Au}^8\) show both ICF and CF components having peaks at the cumulative catcher thicknesses at \( \approx 145 \pm 37, 168 \pm 20 \) and \( 200 \pm 35 \) \( \mu g/cm^2 \) (due to \(^{12}\text{C}-\text{fusion} \)) and at \( \approx 275 \pm 60, 256 \pm 37 \) and \( 290 \pm 47 \) \( \mu g/cm^2 \) (due to \(^{16}\text{O}-\text{fusion} \)) at three different
Figure 5.4.4: Experimentally measured forward recoil range distributions for $^{193}\text{Hg}^8(p3n)$ at projectile energies $\approx 81$, 90 and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
Figure 5.4.5: Experimentally measured forward recoil range distributions for $^{193}{\text{Hg}}^m(p3n)$ at projectile energies $\approx 81, 90$ and $96$ MeV. The lines joining data points are the result of best fit to the experimental data points.
Figure 5.4.6: Experimentally measured forward recoil range distributions for $^{192}$Hg(p4n) at projectile energies $\approx 81, 90$ and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
Figure 5.4.7: Experimentally measured forward recoil range distributions for $^{191}$Hg$(p5n)$ at projectile energies ≈81, 90 and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
Figure 5.4.8: Experimentally measured forward recoil range distributions for $^{191}\text{Hg}^{m}(p5n)$ at projectile energies ≈81, 90 and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
Table 5.1: Experimentally measured forward recoil ranges $R_p$(expt) deduced from RRD curves, and theoretically calculated most probable mean ranges $R_p$(Th) for CF components at ≈ 81, 90 & 96 MeV, in the interaction of $^{16}$O with $^{181}$Ta.

<table>
<thead>
<tr>
<th>Residue</th>
<th>Energy (E) ≈ 81 MeV</th>
<th>Energy (E) ≈ 90 MeV</th>
<th>Energy (E) ≈ 96 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_p$(expt) (µg/cm²)</td>
<td>$R_p$(Th) (µg/cm²)</td>
<td>$R_p$(expt) (µg/cm²)</td>
</tr>
<tr>
<td>$^{194}$Tl(3n)</td>
<td>265±76</td>
<td>267</td>
<td>275±47</td>
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<tr>
<td>$^{193}$Tl(4n)</td>
<td>260±77</td>
<td>267</td>
<td>254±39</td>
</tr>
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<td>$^{192}$Tl(5n)</td>
<td>244±58</td>
<td>267</td>
<td>255±21</td>
</tr>
<tr>
<td>$^{193}$Hg₃(p3n)</td>
<td>261±82</td>
<td>267</td>
<td>257±75</td>
</tr>
<tr>
<td>$^{193}$Hg₅(p3n)</td>
<td>275±75</td>
<td>267</td>
<td>270±60</td>
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<td>$^{192}$Hg(p4n)</td>
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<td>282±57</td>
</tr>
<tr>
<td>$^{191}$Hg₃(p5n)</td>
<td>276±47</td>
<td>267</td>
<td>256±47</td>
</tr>
<tr>
<td>$^{191}$Hg₅(p5n)</td>
<td>249±53</td>
<td>267</td>
<td>230±65</td>
</tr>
</tbody>
</table>

projectile energies i.e., ≈81, 90 & 96 MeV respectively. The contribution of different fusion components ($^{16}$O and/or $^{12}$C) may be obtained by dividing the area under the peak of the corresponding fusion component by the total area associated with the distribution. It may, however, be pointed out that, the relative contribution of $^{12}$C-fusion for the reaction $^{181}$Ta($^{16}$O,αn)$^{192}$Au⁸, [Figs. 5.4.9(a-c)], is found to be ≈20.8%, 11.5% and 23.8% while the contribution from $^{16}$O-fusion is found to be ≈79.2%, 88.5% and 76.2% at three different projectile energies (≈81, 90 & 96 MeV) respectively.

Similar to the $^{192}$Au⁸ residues, in case of the radio-isotopes $^{191}$Au⁸ and $^{190}$Au⁸ populated through the reactions $^{181}$Ta($^{16}$O,α2n) and $^{181}$Ta($^{16}$O,α3n) also show two LMT components in RRD data. In case of the residue $^{191}$Au⁸, peaks at the cumulative catcher thicknesses are found at ≈ 165±27, 170±37 and 204±43 µg/cm² (due to $^{12}$C-fusion) and ≈ 256±48, 281±43 and 294±45 µg/cm² (due to $^{16}$O-fusion) respectively, at three different projectile energies. Further, the relative contribution of $^{12}$C-fusion for the reaction $^{181}$Ta($^{16}$O,α2n)$^{191}$Au⁸, [Figs. 5.4.10(a-c)], is found to be ≈20.5%, 28.6% and 52.5% while the contribution from $^{16}$O-fusion is found to be ≈79.5%,
71.4% and 47.5% at three different projectile energies (81, 90 & 96 MeV) respectively. While, in case of the residues $^{190}$Au, peaks at the cumulative catcher thicknesses are found at $\approx 181\pm22$, $196\pm25$ and $213\pm35$ \(\mu\text{g/cm}^2\) (due to \(^{12}\text{C}-\text{fusion}\)) and at $\approx 290\pm50$, $282\pm35$ and $286\pm51$ \(\mu\text{g/cm}^2\) (due to \(^{16}\text{O}-\text{fusion}\)) at three studied energies $\approx 81$, 90 & 96 MeV. The relative contribution of \(^{12}\text{C}-\text{fusion}\) for the reaction $^{181}\text{Ta}(^{16}\text{O},\alpha 3n)^{190}\text{Au}$, [Figs. 5.4.11(a-c)], is found to be $\approx 11.6\%$, 29.8\% and 35.8\% while the contribution from \(^{16}\text{O}-\text{fusion}\) is found to be $\approx 88.4\%$, 70.2\% and 64.2\% respectively at 81, 90 & 96 MeV beam energies. The observation of peaks at relatively smaller cumulative depths clearly indicates relatively less degrees of LMT involved in the process. The percentage relative contributions for different CF and/or ICF components for the residues populated via $\alpha$-emission channels deduced from RRD data are also indicated in Table 5.2.

The FRRDs for $^{186}\text{Ir}$ residues populated via $2\alpha 3n$ channel, are shown in Figs. 5.4.12(a-c). As can be seen from these figures, the FRRDs may be resolved into three Gaussian peaks, indicating the presence of three different linear momentum transfer components associated with the fusion of $^{16}\text{O}$, $^{12}\text{C}$ and $^{8}\text{Be}$. The reaction products $^{186}\text{Ir}$ may be formed via CF and/or ICF of $^{16}\text{O}$ with $^{181}\text{Ta}$. In case of CF, the composite system $^{197}\text{Tl}$ is formed, which may decay via the statistical emission of two $\alpha$-particles and 3 neutrons leaving behind the above mentioned residue. On the other hand, the residue $^{186}\text{Ir}$ may also be populated, if it is assumed that, the incident $^{16}\text{O}$ ion breaks-up into its fragments (e.g., $^{12}\text{C}$ & $\alpha$ and $^{8}\text{Be}$ & $^{8}\text{Be}$), one of the fragments ($^{12}\text{C}$) fuses with the target nucleus forming an in-completely fused composite system $^{193}\text{Au}$, which decay by the emission of an $\alpha$-particle and three neutrons forming $^{186}\text{Ir}$. Moreover, if $^{8}\text{Be}$ fuses with the target, in-completely fused $^{189}\text{Ir}$ will be formed which may emit three neutrons to leave the residue $^{186}\text{Ir}$. The Fig. 5.4.12 show three LMT components for $^{186}\text{Ir}$ arising out of the three modes of formation. The peaks for these distributions are at $\approx 100\pm27$, $70\pm21$ and $121\pm21$ \(\mu\text{g/cm}^2\) (fusion of $^{8}\text{Be}$), at $\approx 183\pm13$, $166\pm27$ and $213\pm23$ \(\mu\text{g/cm}^2\) (fusion of $^{12}\text{C}$) and $\approx 258\pm38$, $262\pm40$ and $290\pm50$ \(\mu\text{g/cm}^2\) (fusion of $^{16}\text{O}$) at the three respective energies. From the above, it can be inferred that the residues $^{186}\text{Ir}$ produced through $^{181}\text{Ta}(^{16}\text{O}, 2\alpha 3n)$ channel has the contribution from both the processes namely, CF and ICF. Further, the relative contribution of $^{8}\text{Be}$ - fusion for the reaction $^{181}\text{Ta}(^{16}\text{O},2\alpha 3n)^{186}\text{Ir}$, [Figs. 5.4.12(a-c)], is
Figure 5.4.9: Experimentally measured forward recoil range distributions for $^{192}$Au$(\alpha n)$ at projectile energies $\approx$ 81, 90 and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
Figure 5.4.10: Experimentally measured forward recoil range distributions for $^{191}$Au$(\alpha 2n)$ at projectile energies $\approx$81, 90 and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
Figure 5.4.11: Experimentally measured forward recoil range distributions for $^{190}\text{Au}(\alpha 3n)$ at projectile energies ≈ 81, 90 and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
Figure 5.4.12: Experimentally measured forward recoil range distributions for $^{186}$Ir$(2\alpha3n)$ at projectile energies ≈81, 90 and 96 MeV. The lines joining data points are the result of best fit to the experimental data points.
found to be $\approx 21.2\%$, $17.0\%$ and $42.7\%$. Relative contribution for $^{12}$C-fusion in the same reaction, is found to be $\approx 18.0\%$, $23.7\%$ and $35.5\%$ while the contribution from $^{16}$O-fusion is found to be $\approx 60.8\%$, $59.3\%$ and $21.8\%$ at 81, 90 and 96 MeV projectile energies respectively.

In order to get the confidence in the experimentally measured FRRDs, an attempt has been made to theoretically estimate the most probable mean ranges, $R_p(\text{Th})$, using range-energy relation. The experimentally measured most probable mean ranges $R_p(\text{expt})$ for both CF and/or ICF components, in case of $\alpha$-emitting channels are shown in Table 5.3, and are found to agree well, in general, with the theoretically calculated range values within the experimental uncertainties. In Table 5.3, the errors shown in $R_p(\text{expt})$ indicates the FWHM of the Gaussian distribution of the experimental data. It may be observed from the RRD data that in some cases, the peak corresponding to a particular fusion component at higher incident energy is observed at slightly lower thicknesses than the peak at lower beam energy. This may be due to the finite resolution in RRD data and the fact that the catcher foils may also have uncertainty in their thicknesses.

Table 5.2: Relative contributions of CF and ICF processes, at $\approx 81$, 90 and 96 MeV energies, deduced from RRD data.

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<th>Residue</th>
<th>$E_{lab}$ (MeV)</th>
<th>CF of $^{16}$O(%)</th>
<th>ICF of $^{12}$C(%)</th>
<th>ICF of $^{8}$Be(%)</th>
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</thead>
<tbody>
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<td>79.2</td>
<td>20.8</td>
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<tr>
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<td>90</td>
<td>88.5</td>
<td>11.5</td>
<td>-</td>
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<tr>
<td></td>
<td>96</td>
<td>76.2</td>
<td>23.8</td>
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<td>$^{191}$Au$(\alpha 2n)$</td>
<td>81</td>
<td>79.5</td>
<td>20.5</td>
<td>-</td>
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<tr>
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<td>90</td>
<td>71.4</td>
<td>28.6</td>
<td>-</td>
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<tr>
<td></td>
<td>96</td>
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<td>-</td>
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<td></td>
<td>90</td>
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<td></td>
<td>96</td>
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<td>18.0</td>
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</tr>
<tr>
<td></td>
<td>90</td>
<td>59.3</td>
<td>23.7</td>
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</tr>
<tr>
<td></td>
<td>96</td>
<td>21.8</td>
<td>35.5</td>
<td>42.7</td>
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Table 5.3: Experimentally measured $R_p$(expt) deduced from RRD curves and theoretically calculated $R_p$(Th) for ICF components at $\approx$81, 90 and 96 MeV energies.

<table>
<thead>
<tr>
<th>Residue</th>
<th>$R_p$(expt) ($\mu$g/cm$^2$) (CF of $^{16}$O)</th>
<th>$R_p$(Th) ($\mu$g/cm$^2$) (CF of $^{16}$O)</th>
<th>$R_p$(expt) ($\mu$g/cm$^2$) (ICF of $^{12}$C)</th>
<th>$R_p$(Th) ($\mu$g/cm$^2$) (ICF of $^{12}$C)</th>
<th>$R_p$(expt) ($\mu$g/cm$^2$) (ICF of $^{8}$Be)</th>
<th>$R_p$(Th) ($\mu$g/cm$^2$) (ICF of $^{8}$Be)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{192}$Au($\alpha$n)</td>
<td>275±60</td>
<td>267</td>
<td>145±37</td>
<td>198</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{191}$Au($\alpha$2n)</td>
<td>256±48</td>
<td>267</td>
<td>165±27</td>
<td>198</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{190}$Au($\alpha$3n)</td>
<td>290±50</td>
<td>267</td>
<td>181±22</td>
<td>198</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{186}$Ir($2\alpha$3n)</td>
<td>258±38</td>
<td>267</td>
<td>183±13</td>
<td>198</td>
<td>100±27</td>
<td>108</td>
</tr>
<tr>
<td>Energy (E) $\approx$81 MeV</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Energy (E) $\approx$90 MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{192}$Au($\alpha$n)</td>
<td>256±37</td>
<td>287</td>
<td>168±20</td>
<td>215</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{191}$Au($\alpha$2n)</td>
<td>281±43</td>
<td>287</td>
<td>170±37</td>
<td>215</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{190}$Au($\alpha$3n)</td>
<td>282±35</td>
<td>287</td>
<td>196±25</td>
<td>215</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{186}$Ir($2\alpha$3n)</td>
<td>262±40</td>
<td>287</td>
<td>166±27</td>
<td>215</td>
<td>70±21</td>
<td>117</td>
</tr>
<tr>
<td>Energy (E) $\approx$96 MeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{192}$Au($\alpha$n)</td>
<td>290±47</td>
<td>298</td>
<td>200±35</td>
<td>227</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{191}$Au($\alpha$2n)</td>
<td>294±45</td>
<td>298</td>
<td>204±43</td>
<td>227</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{190}$Au($\alpha$3n)</td>
<td>286±51</td>
<td>298</td>
<td>213±35</td>
<td>227</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$^{186}$Ir($2\alpha$3n)</td>
<td>290±50</td>
<td>298</td>
<td>213±23</td>
<td>227</td>
<td>121±21</td>
<td>122</td>
</tr>
</tbody>
</table>

In order to study the energy dependence of CF (full LMT) and ICF (partial LMT) components, percentage relative contributions of the CF and ICF components are plotted against the projectile energy in Figs. 5.4.13(a-b) and Figs. 5.4.14(a-b) for all the four $\alpha$-emitting channels. The overall errors in relative contributions are expected to be less than $\approx$10%. As can be seen from the Fig. 5.4.13 (a) that in case of $\alpha$n channel the relative percentage contribution of CF and ICF remains almost constant. However, it may be observed from Figs. 5.4.13(b) and Figs. 5.4.14(a), in case of $\alpha$2n and $\alpha$3n reaction channels (which are expected to be populated via both CF and/or ICF process), the CF contribution decreases with projectile energy, while the ICF contribution (fusion of $^{12}$C) is found to increase with projectile energy. Further, from Fig. 5.4.14 (b), in case of $2\alpha$3n reaction channel, the relative contribution for the CF of $^{16}$O decreases and the contributions of ICF of $^{16}$O (fusion of $^{12}$C and $^{8}$Be) increases with incident energy. It may, however, be inferred that, in general, ICF starts dominating for individual reaction channels as the projectile energy increases. While deriving the relative contributions from the fitting of RRD data, the value of $\chi^2$ was minimized in the present analysis using a non-linear least-square fit routine.
Figure 5.4.13: Relative strengths of the contribution coming from CF and ICF of $^{16}$O with $^{181}$Ta at projectile energies $\approx$81, 90 & 96 MeV for $^{192}$Au$^8$ ($\alpha$n) & $^{191}$Au$^8$ ($\alpha$2n) reaction products. The lines joining data points are just to guide the eyes.
Figure 5.4.14: Relative strengths of the contribution coming from CF and ICF of $^{16}\text{O}$ with $^{181}\text{Ta}$ at projectile energies $\approx$ 81, 90 & 96 MeV for $^{190}\text{Au}^{8}$ $(\alpha 3n)$ & $^{186}\text{Ir}^{g}$ $(2\alpha 3n)$ reaction products. The lines joining data points are just to guide the eyes.
keeping the width ($\omega_0$) of the distribution as a free parameter and most probable mean range ($R_{\text{m}}$) has been kept at the peak position. As such, only the width remains as a free parameter. Moreover, as indicated in Figs. 5.4.9 to 5.4.12, the RRD for the corresponding residues show more than one LMT components (RRD peaks). In such cases, the experimentally measured normalized yields have been fitted using the multi-peak option. 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 RRD data. In the present work the minimization of $\chi^2$ and selected values of FWHM for the peak in the 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 FRRDs with Gaussian constrained at a range expected for full momentum transfer to estimate their relative contributions. The values of $F_{\text{ICF}}$ deduced from ICF data are plotted as a function of normalized beam energy ($E_{\text{beam}}/\text{CB}$) in Fig. 5.4.15. As can be seen from this figure that the ICF fraction increases with energy rapidly at lower energies, however, at relatively higher energies the $F_{\text{ICF}}$ seems to move towards saturation for $^{16}\text{O}+^{181}\text{Ta}$ system. Further, extrapolation of this 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 $F_{\text{ICF}}$ given in Fig. 5.2.4, 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 reported by Morgenstern et. al [15]. However, their work involved measuring the velocity spectra employing time of flight method in the lighter systems and also at relatively higher energies $\approx 10-25$ MeV/n.

Further, Fig. 5.4.16 shows the ICF contributions of different Au isotopes at three different projectile energies. It may be observed from this figure that the production of $^{190}\text{Au}$ via ICF channel is nearly same at 81, 90 & 96 MeV. However, the production probability of $^{191}\text{Au}$ is largest at 90 MeV and smallest at 96 MeV with some intermediate value at 81 MeV. Further, a comparison of production probability of $^{190,191,192}\text{Au}$ at 81, 90 and 96 MeV indicates that maximum production of $^{192}\text{Au}$ is at 90 MeV and smallest at 81 MeV. However, at 96 MeV it has some intermediate value.
Figure 5.4.15: Deduced percentage ICF fraction ($F_{ICF}$) as a function of normalized projectile energy for the system $^{16}\text{O}+^{181}\text{Ta}$. The lines joining data points are just to guide the eyes.

Figure 5.4.16: ICF contribution of different Au isotopes produced in $^{16}\text{O}+^{181}\text{Ta}$ system at projectile energies $\approx$81, 90 & 96 MeV. The lines joining data points are just to guide the eyes.
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 experiment for this system ($^{16}$O+$^{181}$Ta) is proposed, to have better insight in the reaction mechanism and the associated $\ell$-values in case of CF and ICF processes.

5.5 Analysis using SUMRULE model

As has already been mentioned, it is possible to calculate cross-sections for CF and ICF channels using the SUMRULE model [20]. The underlying assumption in the SUMRULE model is that the ICF channels open only for those partial waves which have $\ell$ values greater than $\ell_{\text{critical}}$, i.e., ($\ell \geq \ell_{\text{critical}}$). On the other hand, partial waves with $\ell < \ell_{\text{critical}}$ values contribute to CF. There are three important parameters in the model viz., the temperature $T$ of the contact zone, the diffuseness $\Delta$ of the $T_\ell$ distribution and the Coulomb interaction radius $R_C$. The values; $T=3.5$ MeV, $\Delta=1.7\hbar$ and $R_C=1.5$ fm have been suggested [21] for these parameters. The reaction residues, experimentally measured range integrated cross-sections obtained from the recoil range distribution data and cross-sections calculated by SUMRULE model for presently measured ICF channels populated in the system $^{16}$O +$^{181}$Ta at $\approx$81, 90 and 96 MeV incident projectile energies are given in Table 5.4. As may be seen from this table, that there is a large discrepancy between the measured and calculated cross-section values for these channels. Wilczynski et. al. [20], tested the SUMRULE model for some reactions at $\approx$10 MeV/nucleon energy and found satisfactory agreement in the calculated and experimental cross-sections. The SUMRULE model calculations, carried out for the present system, which allow the ICF processes only for $\ell > \ell_{\text{crit}}$, underestimates the presently measured ICF cross-section data by a few orders of magnitude. As a typical example the experimentally measured cross-sections $\sigma(\text{expt})$ for ($\alpha$3n) and (2$\alpha$3n) channels are $\approx 64.0 \pm 9.6$ mb and $5.0 \pm 0.7$ mb, however, the theoretically calculated SUMRULE values $\sigma(\text{Th})$, are found to be $1.32 \times 10^{-2}$ mb and $3.02 \times 10^{-3}$ mb at 81 MeV beam energy. These discrepancies may
indicate deviations in the assumptions of the model. Similar deviations have also been found by Parker et al.,[22] in their study on $^{12}$C+$^{51}$V system up to 100 MeV ($\approx$8 MeV/nucleon). The SUMRULE model assumes sharp cut-off $\ell$-values for CF and ICF processes. The possible reason for the disagreement between the presently measured and SUMRULE model calculations for ICF channels may be the non-validity of the concept of critical angular momentum at these low energies. The present findings indicate a diffused boundary in $\ell$-space which may penetrate close to the barrier. The cluster structure of the incident ion may also play an important role in ICF reactions.

Table 5.4: Experimentally measured and theoretically calculated cross-sections using SUMRULE model for the residues populated via \(\alpha xn\) (\(x = 1, 2, 3\) ) and \(2\alpha xn\) (\(x = 3\) ) channels in $^{16}$O+$^{181}$Ta system.

<table>
<thead>
<tr>
<th>Residue(s)</th>
<th>RRD @ 81 MeV</th>
<th>RRD @ 90 MeV</th>
<th>RRD @ 96 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\sigma(\text{expt})) (mb)</td>
<td>(\sigma(\text{Th})) (mb)</td>
<td>(\sigma(\text{expt})) (mb)</td>
</tr>
<tr>
<td>$^{192}$Au(^8) ((\alpha n))</td>
<td>6.0±0.9</td>
<td>0.87</td>
<td>144.0±21.6</td>
</tr>
<tr>
<td>$^{191}$Au(^8) ((\alpha 2n))</td>
<td>11.0±1.65</td>
<td>0.20</td>
<td>46.0±6.9</td>
</tr>
<tr>
<td>$^{190}$Au(^8) ((\alpha 3n))</td>
<td>64.0±9.6×10(^{-2})</td>
<td>1.32×10(^{-2})</td>
<td>36.0±5.4</td>
</tr>
<tr>
<td>$^{186}$Ir(^8) (2(\alpha 3n))</td>
<td>5.0±0.75</td>
<td>3.02×10(^{-3})</td>
<td>4.2±0.63</td>
</tr>
</tbody>
</table>

5.6 Angular distributions

The analysis of EFs for the presently studied system $^{16}$O+$^{27}$Al, as mentioned in Section 4.3, clearly indicates that these reactions have significant contributions from the processes other than that of CF. To confirm the reaction mechanism involved, a specially designed experimental setup was used, as shown in Fig. 2.5 of Chapter II. In this experiment, an Al-target supported by a natural thulium material of thickness \(\approx\)0.48 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 get 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 $^{27}$Al($^{16}$O,2\(\alpha n\))\(^{34}$Cl is shown in Fig. 5.6.1. Two peaks are observed, one around \(0\)^\(^0\) – \(13\)^\(^0\) may be assigned to the residues populated by
complete fusion, and the other peak in the angular range $45^\circ-60^\circ$ may 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 $^{27}\text{Al} (^{16}\text{O}, 2\alpha n)$ could be identified from its energy as well as the half-life of $^{34}\text{Cl}$ residues 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 $^{16}\text{O}$ will show peak 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.

Figure 5.6.1: Measured angular distribution for reaction $^{27}\text{Al} (^{16}\text{O}, 2\alpha n)^{34}\text{Cl}$. The lines joining data points are just to guide the eyes.

However, in case of reactions $^{27}\text{Al} (^{16}\text{O}, 3\alpha 3\text{p})^{28}\text{Mg}$, $^{27}\text{Al} (^{16}\text{O}, 3\alpha 3\text{pn})^{27}\text{Mg}$, $^{27}\text{Al} (^{16}\text{O}, 4\alpha 2\text{pn})^{24}\text{Na}$ and $^{27}\text{Al} (^{16}\text{O}, 4\alpha 3\text{p})^{24}\text{Ne}$, the EF analysis clearly indicated that these residues are not likely to be populated by the CF process as the theoretical calculations based on statistical model give negligible contribution for these reactions. This is further confirmed from the angular distribution measurements, since no $\gamma$-peak corresponding to
these residues has been observed in any of the angular zones. Thus, these residues are not likely to be populated either via complete or in-complete fusion processes. However, these residues may be formed by direct reaction process, where the ejectile takes away a large fraction of the energy and 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.

5.7 A note on spin distributions and feeding intensity profile studies

Apart from obtaining the relative contributions of CF and/or ICF processes in heavy ion reactions and their energy and mass asymmetry dependence, other most debated and still out-standing issues about the ICF reaction dynamics at energies \(\approx 4-7\) MeV/nucleon are i) the estimation of the localization of \(\ell\)-window and ii) to examine the possibility to populate high spin states via ICF. As such, in order to understand above issues two particle \(\gamma\)-co-incidence experiments have been performed [23-25], to draw some co-relations between driving angular momenta and successively opened ICF channels. Details of these experiments, carried out at the IUAC, New Delhi, Pelletron Accelerator Facility, are given elsewhere [23-25]. However, for the sake of completeness a brief description of how the particle \(\gamma\)-co-incidence experiments may give useful information in this regard is given here. The experimental arrangement consists of a Gamma Detector Array (GDA) along with a Charged Particle Detector Array (CPDA). The GDA is an assembly of 12 Compton suppressed high resolution HPGe \(\gamma\)-spectrometers at 45°, 99° and 153° with respect to the beam axis and there are four detectors at each of these angles. However, CPDA is a set of 14 Phoswich detectors housed in a 14-cm diameter scattering chamber, covering nearly 90% of the solid angle. The division of these detectors into forward (F), backward (B) and sideways (S) zones was used to differentiate between forward and backward going \(\alpha\)-particles. The fast \(\alpha\)-particles (due to ICF process) were detected in the forward cone. The in-beam prompt \(\gamma\)-ray spectra have been recorded in multi-parameter mode, which includes different co-incidences like: \(\alpha\) and 2\(\alpha\) detected in backward, forward and 90° angles. Finally, several CF and ICF channels have been identified in co-incidence with forward and backward emitted \(\alpha\)-particles. As a typical example, the experimentally measured spin
distributions for the residues $^{180}\text{Ir}(5\alpha)$, $^{177}\text{Re}(4\alpha)$ and $^{174}\text{Ta}(3\alpha3n)$, in the $^{16}\text{O}+^{169}\text{Tm}$ system, are shown in Figs. 5.7.1 (a) [23]. As can be seen from this figure that the patterns of spin distributions of the residues populated via CF and ICF processes are entirely different. A comparison of the spin distribution of the same residue $^{177}\text{Re}$ identified in coincidence with backward (B) and forward (F) going $\alpha$-particles clearly indicates the entirely different spin distribution patterns, a characteristic of such processes. As can be seen from this figure that the intensity of yrast line transitions decreases gradually with high spin for CF, while in case of ICF, the intensity remains almost constant up to a certain limiting spin value and then decreases rapidly for higher spins, indicating the entirely different de-excitation patterns for CF and ICF from entry state to the yrast line. This implies a rather smooth and broad feeding distribution for “yrast states” in case of CF. However, for ICF channels this distribution must have a ‘narrow window’ meaning thereby a well localized angular momentum region where a given projectile like fragment is emitted in contrast to the large window for fusion reactions. The same is reflected from the feeding intensity profiles shown in Figs. 5.7.1 (b) [23].

The complementary and useful information that can be obtained from the above results is that the value of mean input angular momentum increases with direct $\alpha$-multiplicity in the forward cone, which indicates the competition from successively opened ICF channels for each $\ell$-value above $\ell_{\text{crit}}$ for normal fusion (CF), even at projectile energies $\approx 5-6$ MeV/nucleon. This confirms that the ICF reactions predominantly occur due to the influence of centrifugal potential at higher values of input angular momenta where CF is expected to be dominant. As such, it may not be out of place to mention that the ICF is a natural extension of the fusion processes for those interaction trajectories for which the limit of input angular momenta do not allow the CF to occur. From the analysis of some of our recent experiments [23-25] it has been concluded that ICF can populate a given residue via ICF channel with a relatively large angular momentum compared to that populated via CF process. As such, the study of ICF reactions also opens an opportunity to populate and study the residues with higher spins, even at lower projectile energies. An extension to this work is in progress to obtain better insight into the reaction dynamics and associated $\ell$-values.
Figure 5.7.1 (a) Experimentally measured spin distributions for different residues populated via xn (CF product) and $\alpha xn/\alpha 2\alpha xn$ (both CF and/or ICF products), (b) Deduced feeding intensities of gamma cascades of different ER's expected to be produced via: xn, $\alpha xn$ and/or $2\alpha xn$ channels in $^{16}\text{O}+^{169}\text{Tm}$ system at $\approx5.6$ MeV/nucleon. The lines and curves through data points are drawn to just guide the eyes.
Conclusions and Future Perspectives

In the present work, experiments have been carried out to study the heavy ion reaction dynamics at energies from near the Coulomb barrier to well above it. An attempt has been made to study the CF and ICF of $^{16}$O with $^{181}$Ta, $^{103}$Rh and $^{27}$Al targets. Analysis of data has provided significant information about CF and ICF reactions. To be more specific, in order to study the influence of ICF on CF, the EFs of fourteen radio-nuclides; $^{194}$Tlg, $^{194}$Tlm, $^{193}$Tlg, $^{193}$Tlm, $^{192}$Tlg, $^{192}$Tlm, $^{193}$Hgg, $^{193}$Hgm, $^{192}$Hg, $^{191}$Hgg, $^{191}$Hgm, $^{192}$Au, $^{191}$Au and $^{190}$Au produced in $^{16}$O+$^{181}$Ta system, eight radio-nuclides; $^{115}$Teg, $^{115}$Tem, $^{114}$Te, $^{110}$In g, $^{110}$Inm, $^{108}$In g, $^{108}$Inm and $^{103}$Ag produced in $^{16}$O+$^{103}$Rh system and five radio-nuclides; $^{34}$Cl, $^{28}$Mg, $^{27}$Mg, $^{24}$Na and $^{24}$Ne produced in $^{16}$O+$^{27}$Al system have been measured. The experimentally measured EFs have been compared with the predictions of the theoretical model code PACE4. The measured EFs for xn and pxn channels, likely to be populated by CF process are, in general, well reproduced by the theoretical calculations. However, the enhancement of the experimentally measured production cross-sections over the theoretical model predictions have been observed for most of the $\alpha$-emission channels. The enhancement may not be due to the experimental uncertainties as they have been estimated to be $\leq$15 %. As such, this enhancement has been attributed to the contribution coming from ICF reaction dynamics. Further, in order to understand the influence of ICF on CF, the percentage fraction of in-complete fusion (FICF) has been deduced as a function of beam energy and mass asymmetry of the interacting ions. The FICF has been found to be very sensitive to the projectile energy, and also to the mass asymmetry of interacting partners. Further, the value of FICF is found to be $\approx$4.0% for $^{16}$O + $^{103}$Rh system while for $^{16}$O + $^{181}$Ta system it is found to be around $\approx$12.0% at the same normalized projectile energy (i.e. $E_{\text{beam}}/V_b$ =1.38). This indicates the sensitiveness of FICF on the atomic mass number of the target. In order to have a better insight into mass asymmetry dependence the values of FICF for several projectile-target systems (including some literature results) are compared. In general, the value of FICF is found to increase with the mass asymmetry, separately for $^{16}$O and $^{12}$C projectiles. From the above, it may be inferred that, not only mass asymmetry of interacting partners but the projectile structure also affects the ICF population. Further, the observation of large percentage FICF may be attributed to the prompt break-up of projectile $^{16}$O into its $\alpha$-clusters ($^{12}$C+$^4$He and/or $^8$Be+$^8$Be). The break-up
probability increases with the incident projectile energy, and hence the percentage $F_{ICF}$ may increase with projectile energy. It may also be pointed out that the present observations are in agreement with the systematics presented by Morgenstern et al. [15]. The observation of large percentage $F_{ICF}$ in case of $^{16}$O-projectile as compared to $^{12}$C induced reactions may be because of the fact that the $^{16}$O is assumed to be a group of $4\alpha$-clusters, while $^{12}$C consists only of $3\alpha$-clusters. The above mentioned description/discussion on ICF based on the measurement and analysis of EFs strongly reveals that apart from CF, the ICF is also a process of greater importance at these energies.

In order to study the energy dependence and fusion in-completeness in these processes, the forward recoil range distributions (FRRDs) for the following twelve radio-nuclides: $^{194}$Tl, $^{193}$Tl, $^{192}$Tl, $^{193}$Hg, $^{193}$Hg$^m$, $^{192}$Hg, $^{191}$Hg, $^{191}$Hg$^m$, $^{192}$Au, $^{191}$Au, $^{190}$Au and $^{186}$Ir produced in $^{16}$O+$^{181}$Ta system, at three different projectile energies $\approx$ 81, 90 and 96 MeV have also been measured. Different linear momentum transfer components attributed to the fusion of $^{16}$O and/or of $^{12}$C and/or $^9$Be from $^{16}$O projectile to the target nucleus have been observed. The results presented on the measurement and analysis of forward recoil ranges of heavy reaction products, strongly reveal a significant contribution coming from partial linear momentum transfer of projectile associated with in-complete fusion. An attempt has also been made to obtain the percentage relative contributions of complete and/or in-complete fusion components, which show ICF as a competing mode of reaction at these energies. The break-up fusion model of ICF has been found to explain the measured FRRDs at the energies of interest. Based on RRDs analysis, it may be concluded irrefutably that 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. The experimentally measured most probable recoil ranges $R_p$(expt) have been compared with those estimated by using range energy formulations, and are found to be generally in good agreement. The results obtained clearly indicate the partial fusion of projectile with target nucleus associated with ICF at these energies. Calculations for cross-sections have also been performed using SUMRULE model. The cross-sections for incomplete fusion channels calculated with SUMRULE model are found to be significantly small as compared to the measured values. The large discrepancy for ICF channels may be due to the cluster structure of the
projectile and/or due to the non-validity of the concept of critical angular momentum at these energies. Further, the present findings indicate a defused boundary for $\ell$-values which may penetrate close to the barrier.

Further, angular distributions in the system $^{16}\text{O}+^{27}\text{Al}$ have also been measured. From the study of the angular distributions of the residue, it may be inferred that in the case of complete fusion, the residues are emitted in the forward cone along the beam direction, while for in-complete 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 in-complete fusion processes. The analysis of angular distribution data confirms the presence of significant contribution from the ICF process in the $^{27}\text{Al}(^{16}\text{O}, 2\alpha)^{34}\text{Cl}$ reaction.

As an extension of the present work, it is proposed to carry out some experiments to measure the energy spectra of projectile-like fragments, which is supposed to be an extra degree of freedom to explain the findings of the present work. The extension of the present work at relatively higher energies would also be interesting, and will be helpful for the refinement of the present findings. The data of present measurements may be of use in developing a model for in-complete fusion and also for developing the systematics employing several projectile-target parameters and energies of incident ions.
References


