STUDY OF COMPLETE AND INCOMPLETE FUSION IN REACTIONS INDUCED BY $^{12}$C AND $^{16}$O IONS BELOW 7 MeV/NUCLEON ENERGIES

ABSTRACT

THESIS
SUBMITTED FOR THE AWARD OF THE DEGREE OF
Doctor of Philosophy
IN
PHYSICS

BY
MANOJ KUMAR SHARMA

UNDER THE SUPERVISION OF
DR. B. P. SINGH

DEPARTMENT OF PHYSICS
ALIGARH MUSLIM UNIVERSITY
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2002
Abstract

Rutherford in 1911, carried out a series of experiments by bombarding a piece of gold foil with positively charged particles emitted from the radioactive source and showed that atom consists primarily of empty space surrounding a well defined central core called nucleus with a radius $\approx 10^{-15}$ meter. The discovery of neutron in 1932 established that nuclei are made of neutrons and protons, called nucleons.

In 1919, Rutherford was able to demonstrate the first artificial transmutation by irradiating a thin gold foil with $\alpha$-particles obtained from radioactive source, which opened the new era of research in nuclear physics. There are basically two scientific motivations for the research in nuclear physics, one of them is to get the information about the properties of the nucleus and the other is to understand the behaviour of the constituents of the nucleus. A nuclear reaction may take place when an energetic projectile comes close enough to a target nucleus within the range of nuclear forces, leading to the emission of nuclear particles and/or electromagnetic radiations.

In a nuclear reaction, the properties of the system are well defined and well known before and after the reaction has taken place. However, what happens during the reaction is still not well understood. Being a quantum mechanical process, it cannot be visualized directly. Thus, the theories or nuclear models have been proposed. In 1936, Bohr proposed the compound nucleus (CN) model to explain the nuclear reaction mechanism. According to Bohr, a CN is formed when the incident particle fuses with the target nucleus, sharing its
energy and angular momentum among all nucleons through random collisions till the thermodynamic equilibrium is established. The life time of compound nucleus is long enough $\approx 10^{-16}$ sec. In this model it is assumed that the decay of CN is totally independent of its mode of formation. This is known as Bohr’s independent hypothesis, which says decay of CN is totally determined by its good quantum numbers viz., the excitation energy, angular momentum, spin, parity etc.

In 1950, Ghoshal[1] experimentally verified the validity of Bohr’s independent hypothesis. The compound nucleus reaction mechanism is more appropriate at lower values of excitation energies, however, at relatively higher excitation energies the direct reaction mechanism, in which only a few degrees of freedom are excited, is more likely to occur. The time scales on which these two reaction mechanisms i.e., CN and direct reactions occur are quite different to each other. The time scale of direct reactions is $\approx 10^{-22}$ sec., which is typically the time taken by the energetic projectile to pass through the target nucleus. There are several experimental and theoretical observations[2] which indicate that particles may also be emitted from the excited composite system before the establishment of thermodynamic equilibrium. This is generally referred to as pre-compound or pre-equilibrium (PE) emission.

Several models have been proposed to explain the reaction mechanism. They describe certain aspects of nuclear structure and mechanism, but none of them gives their complete information. More and more experimental data is needed for the better understanding of the reaction mechanism. Thus, the
nuclear physics is still experimental subject to be studied in many respects. During the past decades, major research efforts have gone into the study of nuclei by means of probes which excite the nuclei in a moderate way mainly by bombardment with the beams of protons, neutrons and $\alpha$-particles. Later, the availability of precise beams of heavy ions have opened a new horizon in the study of nuclear structure and nuclear reactions. The two Pelletron accelerators, one at the Nuclear Science Centre (NSC), New Delhi and the other at the Tata Institute of Fundamental Research (TIFR), Mumbai became available for heavy ion (HI) experimental research in our country in early 90's and gave a big boost to the study of HI reactions.

The study of reactions involving heavy ions tend to differ from the light ion induced reactions in many respects. The de-Broglie wavelength associated with relative motion of interacting HI's is much shorter than that for light ions, typically an order of magnitude smaller than the size of nuclei. Since HI's consist of a larger mass in comparison to light ions, the angular momentum of HI's with respect to the centre of mass is very large. Most important feature of HI reactions is, (since a HI is a multi-nucleon system), that a variety of reactions may occur at energies slightly above the Coulomb barrier. Therefore, heavy ion induced reactions give way to the possibility of producing nuclei with high excitation energy and high spin. Nuclei far away from the neutron drip line may also be produced in HI interactions.

The study of heavy ion induced reactions starts with the extrapolations from the existing knowledge of nuclear structure and reactions, their generalization or modification in order to encompass new experimental findings.
Because of the small de-Broglie wavelength of the relative motion $\lambda$ as compared to the nuclear size, one can study heavy ion reactions semi classically. In semi classical approach, the radial motion is treated classically and angular motion is treated in the central field quantum mechanically. In semi classical approach the impact parameter $b$ is related with the minimal distance between the two interacting ions $r_{\text{min}}$ by the relation [3],

$$r_{\text{min}} = \frac{b}{\sqrt{1 - \frac{V(r_{\text{min}})}{E_{\text{CM}}}}}$$  \hspace{1cm} (1)$$

where, $E_{\text{CM}}$ is the center of mass energy and $V(r_{\text{min}})$ is the nuclear potential acting between the two ions.

The collision between interacting ions may be explained by the effective potential depending on distance and relative angular momentum having the form,

$$V_i(r) = V_c(r) + V_n(r) + V_{\text{cent}}(r)$$  \hspace{1cm} (2)$$

where, $V_c(r)$ is the repulsive Coulomb potential and is given by

$$V_c(r) = \frac{1}{4\pi \varepsilon_o} \frac{Z_p Z_T e^2}{r}$$  \hspace{1cm} (3)$$

for $r \geq R_c$

$$V_c(r) = \frac{1}{4\pi \varepsilon_o} \frac{Z_p Z_T e^2}{2R_c} (3 - \frac{r^2}{R_c^2})$$  \hspace{1cm} (4)$$

for $r \leq R_c$.

$V_n(r)$ is the attractive nuclear potential, which may be taken as Woods-Saxon
form given by,

\[ V_n(r) = \frac{V_o}{1 + \exp\left(\frac{r - R}{a}\right)} \]  \hspace{1cm} (5)

where,

\[ R = r_o (A_T^{1/3} + A_P^{1/3}) \]  \hspace{1cm} (6)

and

\[ V_{cent}(r) \] is the repulsive centrifugal potential.

\[ V_{cent}(r) = \frac{\hbar^2 l(l + 1)}{2\mu r^2} \]  \hspace{1cm} (7)

Here, \( Z_P, Z_T \) are the atomic numbers of the projectile and the target nuclei respectively, \( r \) is the relative separation between the interacting ions, \( R_o \) the radius of the target nucleus (assumed spherical), \( l \) the angular momentum, \( \mu \) the reduced mass of the interacting nuclei, \( V_o \) is the depth of the potential, \( a \) is the diffuseness parameter and \( r_o = 1.31 \text{ fm} \).

The two ions may come within the range of nuclear interactions at still lower values of impact parameter. Classically, nuclear reactions may take place if the center of mass energy \( (E_{CM}) \) of the two ions is high enough to overcome the Coulomb barrier. The projectile may fuse with the target and a variety of reactions may occur.

At lower incident energies and for relatively lower values of impact parameter, the projectile may completely fuse with the target nucleus, transferring the total angular momentum to the composite system. This composite system is far from statistical equilibrium as a large part of its excitation energy
is used for an orderly collective translational motion of the nucleons. This complete fusion of heavy ion with the target nucleus is assumed to proceed by a sequence of two-body interactions, which results in the conversion of orderly kinetic energy of the incident ion into chaotic thermal motion of nucleons. The randomization process ends when the composite nucleus reaches a state of thermal equilibrium making it a compound nucleus. Once the thermal equilibrium is achieved, the accumulation of sufficient energy on a single nucleon/cluster may occur by a random sequence of events and particle evaporation may take place after a sufficiently long time.

At relatively higher excitation energies and large impact parameters, the angular momentum of the projectile may be too large for the composite system to hold. In such cases, only a part of the projectile may fuse with the target nucleus and the remaining part is stripped off. This is called incomplete fusion of heavy ion. The angular momentum carried by the composite nucleus now depends on the mass of the fused fragment [4].

Further, at higher excitation energies and low impact parameters, a composite nucleus may be formed and it may happen that during the process of thermalization, nucleons or clusters still possessing considerable energy are emitted into continuum. These nucleons have average energy higher than that of the nucleons evaporated from the compound nucleus and are typically called as pre-equilibrium particles. The incomplete fusion (ICF) may also be looked as a kind of pre-equilibrium reaction where the path of complete fusion (CF) is hindered by the emission of a cluster. Though, PE emissions is likely to be important at higher energies, however, some recent
experiments [5, 6] have indicated that their contributions are significant even at energies only slightly greater than the Coulomb barrier.

There are several techniques for the study of reaction mechanism, at medium and low energies, however, useful information can also be extracted from the study of the measured excitation functions of nuclear reactions induced by heavy ions [2]. In the heavy ion reactions, the final state has a heavy residual nucleus, light ions and/or γ rays. In most of the experiments the properties like, charge, energy distribution, angular distribution etc., of light particles and/or γ rays emitted in such reactions are measured. However, considerable information about the nuclear reaction mechanism may also be obtained by studying the properties of the heavy residues. These heavy residues may be identified by their characteristics like charge and mass using an appropriate recoil mass separator or by measuring their energy loss in a medium along with the time of flight. They may also be identified by their characteristic X-rays and γ rays and, if radioactive, by measuring their half lives.

Activation technique is one of the simplest but powerful method of measuring the excitation functions (EFs) to deduce important information about the nuclear reaction mechanism. In this technique, the activities induced by radioactive fragments in the target and catcher assembly are measured off line. The main advantage of the activation technique is the possibility of measuring excitation functions for the production of a large number of residues in a single irradiation, reducing beam-time requirements.
In the heavy ion reactions at moderate energies, a large number of reaction channels are open and the analysis of excitation functions for these reactions may provide significant information about the complete and incomplete fusion/pre-equilibrium emission. The slowly descending tail of the EFs is one of the important signatures of pre-equilibrium emission.

In the case of complete fusion large momentum is transferred and the composite system recoils in the beam direction to a larger distance. However, in case of incomplete fusion, the fragments recoil at larger angles and hence at distances that become increasingly smaller with the decreasing mass of the fused projectile fragment. As such, information regarding complete and incomplete fusion in heavy ion reactions may be extracted from recoil range measurements of the residues. In the incomplete fusion process, the linear momentum carried by the incident projectile is not transferred completely to the composite nucleus, while in the case of complete fusion the entire linear momentum of the projectile is transferred to the composite nucleus. Some earlier studies [7, 8, 9, 10, 11] showed that a careful recoil range distribution (RRD) study is quite helpful in separating individual contribution of CF and ICF channels even at energies as low as 7 MeV/nucleon. A significant contribution of incomplete fusion to the total reaction cross-section has been observed in these studies.

As part of a program [12, 13, 14, 15] to study CF, ICF and PE emission in heavy ion induced reactions, activation technique has been used to measure the EFs for the reactions

\[ ^{128}Te(^{12}C,3n)^{137m}Ce, \quad ^{128}Te(^{12}C,5n)^{135}Ce, \quad ^{128}Te(^{12}C,p4n)^{135}La, \]
The experiments have been carried out using the HI beams from the Pelletron accelerator at the Nuclear Science, New Delhi, India. The measured EFs for various residues in these systems are compared with the statistical model calculations based on computer codes viz., ALICE-91 [16], CASCADE [17] and PACE2 [18]. These codes do not consider ICF into account. As such the enhancement of experimentally measured EFs as compared to theoretical predications may be attributed to the role played by ICF. Further, to separate out the relative contributions of complete and incomplete fusion in $^{16}O +^{169}Tm$ system at $\approx 87$ MeV, the RRDs of several residues have also been measured. Analysis of the data has indicated significant contribution from ICF for several reaction channels.
References


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TO MY PARENTS
CERTIFICATE

Certified that the work presented in this thesis is the original work of Mr. Manoj Kumar Sharma done under my supervision.

(Dr. B.P. Singh)
ACKNOWLEDGEMENTS

It has indeed been a great fortunate opportunity and profound privilege to have Dr. B. P. Singh as the supervisor of this work. I express my deep sense of gratitude to him and same to Prof. R. Prasad, Chairman and Professor of Experimental Nuclear Physics, Dept. of Physics, A.M.U., for their inspiring, enthusiastic, analytical and critical guidance, constant encouragement and generous support through their intellectual and creative views throughout the work. They always encouraged me to learn various aspect of experimental physics.

Again, I am grateful to Prof. R. Prasad, Chairman, Department of Physics, for extending all the necessary departmental facilities towards this work. I am highly indebted to Prof. Amit Roy, Director and Prof. G. K. Mehta, Former Director, Nuclear Science Centre, New Delhi, India for extending necessary facilities for carrying out this work. I also thank to Dr. A. K. Sinha, Director, IUC-DAEF, Calcutta Centre, Kolkata for the financial support as Junior Research Fellowship (J.R.F.) and Senior Research Fellow (S.R.F.) during the present work and Dr. Sandeep S. Ghugre for encouragement towards this work. Thanks are due to Ms. Unnati, Mr. B. K. Sharma, Dr. Sunita Gupta, Dr. H.D. Bhardwaj, Dr. M. M. Musthafa, Mr. Rakesh Kumar, Ms. K. S. Golda, Mr. S. Muralidhar, Mr. N. Madhavan and Dr. R. K. Bhaumik for their valuable help during the experiments.

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(Manoj Kumar Sharma)
## Contents

<table>
<thead>
<tr>
<th>Chapter I</th>
<th>Introduction</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter II</td>
<td>Experimental Details</td>
<td>16</td>
</tr>
<tr>
<td>2.1</td>
<td>Pelletron accelerator</td>
<td>16</td>
</tr>
<tr>
<td>2.2</td>
<td>Sample preparation</td>
<td>20</td>
</tr>
<tr>
<td>2.3</td>
<td>Irradiation</td>
<td>22</td>
</tr>
<tr>
<td>2.4</td>
<td>Measurement of nuclear reaction cross-section</td>
<td>24</td>
</tr>
<tr>
<td>2.5</td>
<td>Detection of reaction residues</td>
<td>25</td>
</tr>
<tr>
<td>2.6</td>
<td>Calibration and efficiency determination of HPGe detector</td>
<td>29</td>
</tr>
<tr>
<td>2.7</td>
<td>Recoil range distributions</td>
<td>36</td>
</tr>
<tr>
<td>2.8</td>
<td>Experimental uncertainties</td>
<td>39</td>
</tr>
<tr>
<td>Chapter III</td>
<td>Measurements</td>
<td>43</td>
</tr>
<tr>
<td>3.1</td>
<td>$^{12}C+^{28}_{62}Te$ SYSTEM</td>
<td>44</td>
</tr>
<tr>
<td>3.2</td>
<td>$^{16}<em>{8}O+^{150}</em>{68}Tb$ SYSTEM</td>
<td>49</td>
</tr>
<tr>
<td>3.3</td>
<td>$^{16}<em>{8}O+^{169}</em>{69}Tm$ SYSTEM</td>
<td>57</td>
</tr>
<tr>
<td>3.4</td>
<td>Measurement of recoil range distributions</td>
<td>64</td>
</tr>
<tr>
<td>Chapter IV</td>
<td>Computer Codes</td>
<td>68</td>
</tr>
<tr>
<td>4.1</td>
<td>ALICE-91</td>
<td>68</td>
</tr>
<tr>
<td>4.2</td>
<td>CASCADE</td>
<td>71</td>
</tr>
<tr>
<td>4.3</td>
<td>PACE2</td>
<td>75</td>
</tr>
<tr>
<td>Chapter V</td>
<td>Results and Discussion</td>
<td>79</td>
</tr>
<tr>
<td>5.1</td>
<td>Analysis with code ALICE-91</td>
<td>80</td>
</tr>
<tr>
<td>5.2</td>
<td>Analysis with code CASCADE</td>
<td>84</td>
</tr>
<tr>
<td>5.3</td>
<td>Analysis with code PACE2</td>
<td>87</td>
</tr>
<tr>
<td>5.4</td>
<td>Recoil range distributions</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>List of publications</td>
<td>94</td>
</tr>
</tbody>
</table>
Chapter I
Introduction

Rutherford in 1911, carried out a series of experiments by bombarding a piece of gold foil with positively charged particles emitted from the radioactive source and showed that atom consists primarily of empty space surrounding a well defined central core called nucleus with a radius \( \approx 10^{-15} \) meter. The discovery of neutron in 1932 established that nuclei are made of neutrons and protons, called nucleons.

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In a nuclear reaction, the properties of the system are well defined and well known before and after the reaction has taken place. However, what happens during the reaction is still not well understood. Being a quantum mechanical process, it can not be visualized directly. Thus, the theories or nuclear models have been proposed. In 1936, Bohr proposed the compound nucleus (CN)
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In 1950, Ghoshal[1] experimentally verified the validity of Bohr’s independent hypothesis. The compound nucleus reaction mechanism is more appropriate at lower values of excitation energies, however, at relatively higher excitation energies the direct reaction mechanism, in which only a few degrees of freedom are excited, is more likely to occur. The time scales on which these two reaction mechanisms i.e., CN and direct reactions occur are quite different to each other. The time scale of direct reactions is $\approx 10^{-22}$ sec., which is the time taken by the energetic projectile to pass through the target nucleus. There are several experimental and theoretical observations[2] which indicate that particles may also be emitted from the excited composite system before the establishment of a thermodynamic equilibrium. This is generally referred to as pre-compound or pre-equilibrium (PE) emission.

Several models have been proposed to explain the reaction mechanism. They describe certain aspects of nuclear structure and mechanism, but none of them gives their complete information. More and more experimental data
is needed for the better understanding of the reaction mechanism. Thus, the nuclear physics is still experimental subject to be studied in many respects. During the past decades, major research efforts have gone into the study of nuclei by means of probes which excite the nuclei in a moderate way mainly by bombardment with the beams of protons, neutrons and α-particles. Later, the availability of precise beams of heavy ions have opened a new horizon in the study of nuclear structure and nuclear reactions. The two Pelletron accelerators, one at the Nuclear Science Centre (NSC), New Delhi and the other at the Tata Institute of Fundamental Research (TIFR), Mumbai became available for heavy ion (HI) experimental research in our country in early 90’s and gave a big boost to the study of HI reactions.

There is no well defined border line between light and heavy ions, the $A = 4$ (i.e., $^4He$) has sometimes been referred to as the "lightest heavy ion" [3]. The study of reactions involving heavy ions tend to differ from the light ion induced reactions in many respects. The de-Broglie wavelength associated with relative motion of interacting HI’s is much shorter than that for light ions, typically an order of magnitude smaller than the size of nuclei. Since HI’s consist of a larger mass in comparison to light ions, the angular momentum of HI’s with respect to the centre of mass is very large. Most important feature of HI reactions is, (since a HI is a multi-nucleon system), that a variety of reactions may occur at energies slightly above the Coulomb barrier. Therefore, heavy ion induced reactions give way to the possibility of producing nuclei with high excitation energy and high spin. Nuclei far away from the neutron drip line may also be produced in HI interactions.
Thus, it allows the study of nuclear matter in the conditions that do not exist naturally. Heavy ion induced reactions in principle can also be used to produce super heavy elements (SHE).

The study of heavy ion induced reactions starts with the extrapolations from the existing knowledge of nuclear structure and reactions, their generalization or modification in order to encompass new experimental findings. Because of the small de-Broglie wavelength of the relative motion $\lambda$ as compared to the nuclear size, one can study heavy ion reactions semi classically. In semi classical approach, the radial motion is treated classically and angular motion is treated in the central field quantum mechanically. In semi classical approach the impact parameter $b$ is related with the minimal distance between the two interacting ions $r_{\text{min}}$ by the relation [3],

$$r_{\text{min}} = \frac{b}{\sqrt{1 - \frac{V(r_{\text{min}})}{E_{CM}}}}$$  \hspace{1cm} (1)

where, $E_{CM}$ is the center of mass energy and $V(r_{\text{min}})$ is the nuclear potential acting between the two ions.

In one dimensional barrier penetration model no conversion of either relative kinetic energy or the angular momentum into excitation of the internal degrees of freedom of the colliding nuclei is considered in the approach phase. It also assumes that once the system passes over the Coulomb barrier, fusion is possible. In HI reactions, depending on the impact parameter involved a variety of reactions may take place. A typical classical picture of heavy ion reactions is shown in Fig. 1.1 [3]. Some of the important processes
are, elastic scattering (the Coulomb region with $r_{\text{min}} > R_N$), deep inelastic scattering and incomplete fusion (region with $R_F < r_{\text{min}} \leq R_{\text{DIC}}$), transfer reactions (the peripheral region with $R_{\text{DIC}} < r_{\text{min}} \leq R_N$) and fusion reactions (the fusion region with $0 \leq r_{\text{min}} \leq R_F$), where, $R_F$ is the fusion radius $\approx 1.0(A_1^{1/3} + A_2^{1/3})$. In a heavy ion reaction, when the center of mass energy of the partners is greater than the Coulomb barrier, they overcome the barrier and may lose some of the relative energy through friction to get trapped in the pocket of the potential and ultimately it may lead to the formation of the compound nucleus.

![Diagram showing trajectories of peripheral, distant, grazing, and close collisions](image_url)

**Fig 1.1** Trajectories showing peripheral, distant, grazing and close collisions in the classical picture of heavy ion reactions.
The partial reaction cross-section for such a collision at a given energy \( E \) may be given by [3],

\[
\sigma_i^{R}(E) = \pi \lambda^2 (2l + 1) T_i(E)
\]  

(2)

where, \( T_i(E) \) is the transmission coefficient for the potential \( V_i(r) \) at energy \( E \). In its simplest form one may assume a nuclear potential which depends on the relative separation \( r \) of two nuclei. The collision between interacting ions may be explained by the effective potential depending on distance and relative angular momentum having the form,

\[
V_i(r) = V_c(r) + V_n(r) + V_{cent}(r)
\]  

(3)

where, \( V_c(r) \) is the repulsive Coulomb potential and is given by

\[
V_c(r) = \frac{1}{4\pi\varepsilon_o} \frac{Z_p Z_e e^2}{r}
\]  

for \( r \geq R_c \)

\[
V_c(r) = \frac{1}{4\pi\varepsilon_o} \frac{Z_p Z_e e^2}{2R_c} \left(3 - \frac{r^2}{R_c^2}\right)
\]  

(5)

for \( r \leq R_c \).

\( V_n(r) \) is the attractive nuclear potential, which may be taken as Woods-Saxon form given by,

\[
V_n(r) = \frac{V_o}{1 + \exp\left(\frac{r - R}{a}\right)}
\]  

(6)

where,

\[
R = r_o (A_f^{1/3} + A_p^{1/3})
\]  

(7)
and

\[ V_{\text{cent}}(r) = \frac{\hbar^2 l(l + 1)}{2\mu r^2} \]  

(8)

Here, \( Z_P, Z_T \) are the atomic numbers of the projectile and the target nuclei respectively, \( r \) is the relative separation between the interacting ions, \( R_c \) the radius of the target nucleus (assumed spherical), \( l \) the angular momentum, \( \mu \) the reduced mass of the interacting nuclei, \( V_0 \) is the depth of the potential, \( a \) is the diffuseness parameter and \( r_o=1.31 \text{ fm} \). Graphical plots of effective potential as a function of relative separation between incident ions for one of the systems \((^{16}O+^{169}Tm)\) used for different values of \( l \) are shown in Fig. 1.2.

As can be noted from the figure, for the smaller angular momenta \( l \), there is a pocket in the effective potential which decreases with increasing \( l \) and disappears at \( l_{\text{crit}} \). It is assumed that the fusion between the two heavy ions may occur only for those partial waves which allow the two ions to come sufficiently close to get trapped in the potential pocket.

At lower excitation energies, when the two interacting ions pass each other with large impact parameter, they interact only through their Coulomb fields and elastic scattering may take place as only \( V_c \) and \( V_{\text{cent}} \) are important. For grazing impact parameters \( b_{gr} \), processes like inelastic scattering and nucleon transfer may take place. On further reduction of impact parameter the wave functions of the two interacting nuclei overlap considerably and the relative kinetic energy is converted into internal excitation before the two separate out.
Fig. 1.2 Effective potential for $^{16}$O+$^{169}$Tm as a function of relative separation between the ions for different values of angular momentum $l$. 
into target and projectile like systems. These are deep inelastic processes and are likely to take place at energies of a few MeV/nucleon above the Coulomb barrier. The two ions may come within the range of nuclear interactions at still lower values of impact parameter. Classically, nuclear reactions may take place if the center of mass energy ($E_{CM}$) of the two ions is high enough to overcome the Coulomb barrier. The projectile may fuse with the target and a variety of reactions may occur.

At lower incident energies and for relatively lower values of impact parameter, the projectile may completely fuse with the target nucleus, transferring the total angular momentum to the composite system. This composite system is far from statistical equilibrium as a large part of its excitation energy is used for an orderly collective translational motion of the nucleons. This complete fusion of heavy ion with the target nucleus is assumed to proceed by a sequence of two-body interactions, which results in the conversion of orderly kinetic energy of the incident ion into chaotic thermal motion of nucleons. The randomization process ends when the composite nucleus reaches a state of thermal equilibrium making it a compound nucleus. Once the thermal equilibrium is achieved, the accumulation of sufficient energy on a single nucleon/cluster may occur by a random sequence of events and particle evaporation may take place after a sufficiently long time.

At relatively higher excitation energies and large impact parameters, the angular momentum of the projectile may be too large for the composite system to hold. In such cases, only a part of the projectile may fuse with the target nucleus and the remaining part is stripped off. This is called incom-
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Further, at higher excitation energies and low impact parameters, a composite nucleus may be formed and it may happen that during the process of thermalization, nucleons or clusters still possessing considerable energy are emitted into continuum. These nucleons have average energy higher than that of the nucleons evaporated from the compound nucleus and are typically called as pre-equilibrium particles. The incomplete fusion (ICF) may also be looked as a kind of pre-equilibrium reaction where the path of complete fusion (CF) is hindered by the emission of a cluster. Though, PE emissions is likely to be important at higher energies, however, some recent experiments [5, 6] have indicated that their contributions are significant even at energies only slightly greater than the Coulomb barrier. For the values of angular momentum greater than critical value $I_{\text{crit}}$, the composite system breaks apart instead of fusing. As is clear from the above, angular momentum plays a very important role in heavy ion reactions. The $l$ -dependence of partial cross section is shown in Fig. 1.3.

There are several techniques for the study of reaction mechanism, at medium and low energies, however, useful information can also be extracted from the study of the measured excitation functions of nuclear reactions induced by heavy ions [2]. In the heavy ion reactions, the final state has a heavy residual nucleus, light ions and/or $\gamma$ rays. In most of the experiments the properties like, charge, energy distribution, angular distribution etc., of light particles and/or $\gamma$ rays emitted in such reactions are measured. However,
considerable information about the nuclear reaction mechanism may also be obtained by studying the properties of the heavy residues. These heavy residues may be identified by their characteristics like charge and mass using an appropriate recoil mass separator or by measuring their energy loss in a medium along with the time of flight. They may also be identified by their characteristic X-rays and γ rays and, if radioactive, by measuring their half lives.

Fig 1.3 The $l$ dependence of partial cross section for compound nucleus formation, deep inelastic collision, direct reactions, Coulomb excitation and elastic processes. The solid lines represents the geometrical partial cross section $2\pi l/k^2$. The vertical dashed line represent the extension of various $l$ windows in a sharp cut off model.
Activation technique is one of the simplest but powerful method of measuring the excitation functions (EFs) to deduce important information about the nuclear reaction mechanism. In this technique, the activities induced by radioactive fragments in the target and catcher assembly are measured off line. The main advantage of the activation technique is the possibility of measuring excitation functions for the production of a large number of residues in a single irradiation, reducing beam-time requirements.

In the heavy ion reactions at moderate energies, a large number of reaction channels are open and the analysis of excitation functions for these reactions may provide significant information about the complete and incomplete fusion/pre-equilibrium emission. The slowly descending tail of the EFs is one of the important signatures of pre-equilibrium emission. Vergani et al.,[5] have measured the EFs for the production of a large number of isotopes in the interaction of $^{12}C$ with $^{197}Au$ at energies below 10 MeV/nucleon using activation technique. Crippa et. al.,[4] and Tomar et. al.,[8] have also measured the EFs for CF and ICF in heavy ion reactions for different systems. From the analysis of EFs, it has been shown that the ICF process has a substantial contribution to the reaction cross-section. Though, several measurements are available in literature on the study of CF and ICF but the data is still scarce. In order to have a better understanding of these processes, more experimental data covering a wide range of the periodic table and energy is required.

In the case of complete fusion large momentum is transferred and the composite system recoils in the beam direction to a larger distance. However,
in case of incomplete fusion, the fragments recoil at larger angles and hence at distances that become increasingly smaller with the decreasing mass of the fused projectile fragment. As such, information regarding complete and incomplete fusion in heavy ion reactions may be extracted from recoil range measurements of the residues. In the incomplete fusion process, the linear momentum carried by the incident projectile is not transferred completely to the composite nucleus, while in the case of complete fusion the entire linear momentum of the projectile is transferred to the composite nucleus. Some earlier studies [7, 8, 9, 10, 11] showed that a careful recoil range distribution (RRD) study is quite helpful in separating individual contribution of CF and ICF channels even at energies as low as 7 MeV/nucleon. A significant contribution of incomplete fusion to the total reaction cross-section has been observed in these studies.

In this work, as part of a program [12, 13, 14, 15] to study CF, ICF and PE emission in heavy ion induced reactions, activation technique has been used to measure the EFs for several reactions in $^{12}$C+$^{128}$Te, $^{16}$O+$^{159}$Tb, and $^{16}$O+$^{169}$Tm systems at energies near and well above the Coulomb barrier. The experiments have been carried out using the HI beams from the Pelletron accelerator at the Nuclear Science, New Delhi, India. The measured EFs for various residues in these systems are compared with the statistical model calculations based on computer codes viz., ALICE-91 [16], CASCADE [17] and PACE2 [18]. Further, to separate out the relative contributions of complete and incomplete fusion in $^{16}$O+$^{169}$Tm system at $\approx$ 87 MeV, the RRDs of several residues have also been measured. The details of the ex-
Experiments and measurements are given in Chapters II and III, respectively. Chapter IV is devoted to the description of computer codes. The results and analysis of the present measurements are presented in Chapter V. The references are given at the end of each Chapter.
References


Chapter II
Experimental Details

In the present work, activation technique has been used for measuring the excitation functions (EFs) for a large number of evaporation residues produced in $^{12}\text{C}+^{128}\text{Te}$, $^{16}\text{O}+^{159}\text{Tb}$ and $^{16}\text{O}+^{169}\text{Tm}$ systems at the energies below 7 MeV/nucleon. The measured EFs have been compared with theoretical calculations done using three different codes viz., ALICE-91[1], CASCADE[2] and PACE2[3]. Brief details of these codes are given in Chapter IV of the thesis. In the case of $^{16}\text{O}+^{169}\text{Tm}$ system, to separate out the relative contributions of complete and incomplete fusion, the recoil range distributions of various evaporation residues have also been measured at $\approx 87$ MeV. The experiments have been carried out using the 15 UD Pelletron accelerator facility of the Nuclear Science Center (NSC), New Delhi, India.

2.1 Pelletron accelerator

A schematic diagram of NSC Pelletron accelerator is shown in Fig. 2.1.1. The NSC Pelletron is a 15UD, tandem Van de Graff electrostatic accelerator. It is capable of accelerating any ion from proton to uranium (except the inert gases) in the energy range from a few tens of MeV to a few hundred MeV, depending on the ion species. The accelerator is installed in a vertical geometry in a stainless steel tank which is 26.5 meter high and 5.5 meter in diameter. In the middle of the tank there is a high voltage terminal which can hold potential from 4 to 16 MV.
Fig. 2.1.1 A schematic diagram of NSC Pelletron accelerator.
The terminal is connected to the tank vertically with ceramic-titanium accelerating tubes. The tank is filled with a high dielectric constant SF₆ gas at 6-7 atmospheric pressure to insulate the high voltage terminal from the tank wall. A potential gradient is maintained through the accelerating tubes from the ground potential, and from the terminal to the ground potential at the bottom of the tank. Negative ions of suitable energy from Source of Negative Ion by Cesium Sputtering (SNICS) ion source are injected into the accelerator and are accelerated towards the positive terminal. In the first stage of acceleration, the singly charged negative ions from the ion source are accelerated from ground potential to the terminal at high positive potential $V$. The energy gained in the process is $eV$. The beam is then made to pass through a stripper foil where the ions are stripped off the electrons thereby making them positive ions. The average charge of the ion depends upon the type of the ion and the terminal voltage. If $q$ is the charge on the positive ions after passing through the stripper foil, the energy gained by accelerating it from the terminal to the ground potential is $qeV$. Thus, after passing through the two stages of the acceleration, the final energy of the ion in electron volts is given by,

$$E = (q + 1)eV$$  \hspace{1cm} (1)

These high energy ions are then passed through the analysing magnet and an energy slit which selects the particular ions of the desired energy. The beam of ions are then directed towards the desired experimental area with the help of a seven port switching magnet. A schematic diagram of different beam lines at NSC Pelletron facility is shown in Fig. 2.1.2.
Fig. 2.1.2 A schematic diagram of different beam lines at NSC Pelletron facility
2.2 Sample preparation

The samples used in the present work, were either self-supporting or prepared by vacuum evaporation on thin Al-foils. The self supporting $^{159}Tb$ targets were prepared by rolling of natural terbium foils (purity $\approx 99.99\%$). The $^{128}Te$ (enrichment $\approx 87\%$) and natural $^{169}Tm$ targets were prepared by vacuum evaporation technique. This technique is most commonly used for thin film target preparation. In this technique, the material to be deposited is heated to a high temperature in an evacuated chamber and is condensed on a suitable substrate. A schematic diagram of the high vacuum system used in the present work is shown in Fig. 2.2.

The thickness of each target was determined by the $\alpha$ transmission method which is based on the measurement of the energy lost by $\alpha$ particles while passing through the sample. The $5.485 \text{ MeV } \alpha$-particles from $^{241}Am$ source were used for this purpose. The thicknesses of the self-supporting $^{159}Tb$ samples were $\approx 1.7 \text{ mg/cm}^2$, while that of $^{169}Tm$ deposited on thin Al-foils ($\approx 1.5 \text{ mg/cm}^2$) were $\approx 0.6 \text{ mg/cm}^2$. The thicknesses of $^{128}Te$ deposited on 6.75 mg/cm$^2$ Al-foils were $\approx 0.9 \text{ mg/cm}^2$. The Al-backing in case of $^{128}Te$ and $^{169}Tm$ samples served as energy degrader as well as catcher foils, so that recoiling residues may be trapped in catcher thickness. In case of $^{169}Tm$, self-supporting Al-foils of suitable thicknesses were used as catcher foils behind the target, which also served as energy degrader. The samples were cut in size of $1.2 \times 1.2 \text{ cm}^2$ each and were pasted on Al-holders having concentric holes of 1.0 cm diameter. The Al-holders were used for rapid heat dissipation.
Fig. 2.2 A schematic diagram of the high vacuum system
2.3 Irradiation

The irradiations have been performed in the General Purpose Scattering Chamber (GPSC) of 1.5 m diameter having in-vacuum transfer facility. The delay time between the stop of irradiation and the beginning of counting was minimised using in-vacuum transfer of samples. The targets backed by thick Al-catcher were placed normal to the beam direction so that the recoiling nuclei coming out of the target may be trapped in the catcher foil. A stack of four $^{128}Te$ samples was irradiated by $^{12}C^{5+}$ beam at 82 MeV. The energy on each sample was calculated using the stopping power tables of Northcliffe and Schilling [4]. The incident energies on $^{128}Te$ foils were 42.2, 57.7, 70.2 and 82 MeV. The samples of $^{159}Tb$ and $^{169}Tm$ were irradiated using $^{16}O^{5+}$ beam. In case of $^{159}Tb$, two stacks of four samples each were irradiated at 90 and 95 MeV, respectively. For $^{169}Tm$, again two stacks of four samples each were prepared and irradiated at 92 and 95 MeV, respectively. The advantage of the stacked foil technique is that in a single irradiation several foils may be bombarded by the beam of different energies. In case of first $^{159}Tb$ stack irradiated at 90 MeV, the incident energies on different foils were 65.5, 75.2, 83.2 and 90 MeV. However, in the second stack irradiated at 95.0 MeV, the incident energies on different foils were 69.3, 78.7, 87.2 and 95.0 MeV. Thus the two stacks irradiated at 90 and 95 MeV covered a large energy range from $\approx 65$ to 95 MeV. Similarly, in case of $^{169}Tm$ stacks energy range from $\approx 71$ to 95 MeV was covered. Keeping in view the half lives of interest, the irradiations were carried out for $\approx 8$ hours duration each. The beam current was $\approx 30$ to 50 nA. The total charge collected in the Faraday cup has been
used to calculate the flux of the beam. The typical experimental set up used in the present measurements is shown in Fig. 2.3.

Fig. 2.3 The typical experimental set up for heavy ion irradiation
2.4 Measurement of nuclear reaction cross-section

If an incident particle $a$ hits a target nucleus $X$ emitting a particle of type $b$ leaving behind the residual nucleus $Y$, then the reaction may be represented as,

$$a + X \rightarrow Y + b$$

(2)

In abbreviated form it may be represented as $X(a, b)Y$. The cross-section $\sigma_r$ for a particular reaction is given by,

$$\sigma_r = \frac{\text{Number of events } X(a, b)Y/\text{area}}{N_o \phi t}$$

(3)

where, $N_o$ is the number of target nuclei, $\phi$ the beam flux and $t$ is the time of irradiation. If the residual nucleus $Y$ is radioactive, then the number of events $X(a, b)Y$ may be deduced from the activity induced in the sample. At a given beam energy, in the laboratory frame, the reaction cross section is given by the formula [5],

$$\sigma_r(E) = \frac{A\lambda \exp(\lambda t_2)}{N_o \phi \theta K(Ge)[1 - \exp(-\lambda t_1)][1 - \exp(-\lambda t_3)]}$$

(4)

where, $A$ is the total observed counts during the accumulation time $t_3$ of the induced activity of decay constant $\lambda$, $N_o$ the number of target nuclei irradiated for time $t_1$ with a particle beam of flux $\phi$, $t_2$ the time lapse between
the stop of irradiation and the start of counting, \( \theta \) the branching ratio of the characteristic \( \gamma \) ray and \( G \varepsilon \) the geometry dependent efficiency of the detector. The factor \( [1 - \exp(-\lambda t_1)] \) takes care of the decay of evaporation residue during the irradiation and is typically known as the saturation correction. The correction 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 is taken into account via the factors \( \exp(\lambda t_2) \) and \( [1 - \exp(-\lambda t_3)] \) respectively. \( K \) is the correction for the self absorption of the \( \gamma \) radiation in the sample itself and is given by \( [1 - \exp(-\mu d)/\mu d] \), here \( d \) is the thickness of the sample and \( \mu \) is the \( \gamma \) ray absorption coefficient.

### 2.5 Detection of reaction residues

The composite system formed following complete and/or incomplete fusion, may in general decay by emitting one or more neutrons, protons and/or \( \alpha \)-particles, leaving behind the residues which are generally in the excited states. These excited residues decay to the ground states by emitting characteristic \( \gamma \) rays. In order to determine the fusion cross sections in the case of evaporation residue formation, two methods may be used. One is IN-BEAM method in which the residual nuclei may be identified directly from the charge to mass ratio and the other is OFF-BEAM method in which the residual nuclei may be identified by their characteristic \( \gamma \) radiations. Each radioactive isotope has a unique decay mode and that provides a specific way for its identification. Thus, the observed intensity of induced activity is measure of the production of that particular evaporation residue. The main advantage of this method being the relatively low background as compared
to that of the on line measurements and hence better sensitivity. Further, as already mentioned, the cross sections for several reactions can be determined in a single irradiation and hence it is less expensive and less time consuming also. Proper choice of projectile-target combination, incident energy, duration of irradiation, half lives of induced activities and good detectors are some of the basic requirements for accurate measurements by the activation technique.

The activation method involves identification and the measurement of the intensity of the characteristic \(\gamma\) rays emitted by the excited residual nucleus or by the daughter nucleus in the case of radioactive evaporation residues. Several activities may be induced in the sample and the catcher foil by irradiating them with the flux of heavy ions. The irradiation may be followed by off line measurement of the activities induced in the target and catcher assembly. In such measurements, the \(\gamma\) ray spectra of each irradiated sample were recorded at increasing times and radioactive residues were identified by their characteristic \(\gamma\) radiations as well as by their half lives. In some cases, \(\gamma\) rays emitted by two different residues were of nearly same energy. The concentration of each isotope in such cases was separated on the basis of their half lives, by following the induced activities for a considerably long period.

Some of the radioactive residues are produced independently (independent yield) in the interaction of heavy ions. Some of them are also produced in the decay of higher charge isobar precursor (cumulative yield) nucleus through \(\beta^+\) emission, and/or electron capture. For such cases, cumulative
cross sections has been measured if the half life of the precursor is considerably smaller than that of the residue, by analyzing the induced activities at times greater than about eight to ten half lives of the precursors. The cumulative cross section of the given residue is the sum of (i) its independent production cross section and (ii) cross section for the independent production of its precursor multiplied by a numerical coefficient which depends on the branching ratio for precursor decay to residue and the half lives of the precursor and the residue. In such cases, the following decay analysis given by Cavinato et. al.,[6] has been used in order to obtain the precursor decay contributions.

If a precursor \( P \) is formed with cross section \( \sigma_P \) during the irradiation, and decays with half life \( T_{1/2}^P \) and a branching ratio \( P_P \), to a daughter nucleus \( D \) which is produced with cross section \( \sigma_D \) during the irradiation and decays with half life \( T_{1/2}^D \), the cumulative cross section \( \sigma_C \), for the production of the daughter is given by,

\[
\sigma_C = \sigma_D + P_P \frac{T_{1/2}^D}{T_{1/2}^P} \sigma_P
\]  

The branching ratio \( P_P \) has been taken from reference [7]. In some cases, the radioactive residues emit \( \gamma \)-rays of more than one energy. In such cases, the intensities of several gamma rays emitted from the same residue have been recorded and the cross-section for the production of the residue has been calculated from the observed intensities of these gamma-rays separately. The weighted average of these calculated values is then taken as the measured
cross-section.

Following formulation [8] has been used for determining the weighted average.

If \( X_1 \pm \Delta X_1, \ X_2 \pm \Delta X_2, \ X_3 \pm \Delta X_3, \ldots \) are the different measured values of the same quantity, then the weighted average is given as,

\[
\bar{X} = \frac{\sum W_i X_i}{\sum W_i}
\]

(6)

here,

\[
W_i = \frac{1}{\Delta X_i^2}
\]

(7)

and the internal error (I.E.) is given by,

\[
I.E. = [\sum W_i]^{-1/2}
\]

(8)

while the external error (E.E.) is given by,

\[
E.E. = \left[\frac{\sum W_i (\bar{X} - X_i)^2}{n(n-1)\sum W_i}\right]^{1/2}
\]

(9)

Equation (8) depends entirely on the errors of individual observations, whereas equation (9) depends also upon the differences between observations from the mean value. As such the internal error depends on the internal consistency,
whereas the external error is a function of what might be called the external consistency of the observations. A computer programme EXPSIGMA based on the above formulation has been used for computation of cross-sections at various energies.

### 2.6 Calibration and efficiency determination of HPGe detector

In order to identify the characteristic $\gamma$ rays of evaporation residues in the complex $\gamma$ ray spectra, a detector of good resolution and proper calibration is required. The activities induced in the irradiated samples were analysed for several days using CANBERRA High Purity Germanium (HPGe) Detector (resolution $\approx 2$ keV for $1.33$ MeV $\gamma$ ray of $^{60}$Co) of 100 c.c. active volume coupled to a PC through CAMAC based FREEDOM software. The HPGe detector was pre-calibrated using various standard $\gamma$ sources i.e., $^{22}$Na, $^{54}$Mn, $^{57}$Co, $^{60}$Co, $^{133}$Ba, $^{137}$Cs and $^{152}$Eu of known strengths.

The geometry dependent efficiency ($Ge$) of the detector at a given energy was calculated using the expression,

$$Ge = \frac{N_o}{N_{ao}e^{(-\lambda t)}\theta}$$

where, $N_o$ is the disintegration rate of the standard $\gamma$ source at the time of measurement, $N_{ao}$ is the disintegration rate at the time of manufacture, $\lambda$ is the decay constant, $t$ is the time lapse between the manufacture of the source and the start of counting, $\theta$ is the branching ratio of the characteristic $\gamma$ ray.
The prominent γ rays of $^{152}\text{Eu}$ used for the calibration in the present measurements along with their absolute intensities are listed in Table 2.6.

<table>
<thead>
<tr>
<th>γ ray energy (keV)</th>
<th>Absolute Intensity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>121.78</td>
<td>28.40</td>
</tr>
<tr>
<td>244.69</td>
<td>7.51</td>
</tr>
<tr>
<td>344.29</td>
<td>26.60</td>
</tr>
<tr>
<td>443.89</td>
<td>2.80</td>
</tr>
<tr>
<td>778.92</td>
<td>12.98</td>
</tr>
<tr>
<td>964.11</td>
<td>14.50</td>
</tr>
<tr>
<td>1112.08</td>
<td>13.60</td>
</tr>
<tr>
<td>1299.16</td>
<td>1.63</td>
</tr>
<tr>
<td>1408.00</td>
<td>20.80</td>
</tr>
</tbody>
</table>

In the present measurements, the standard γ-sources and the irradiated samples and/or catcher foils were counted in the same geometry. However, the source-detector distance for various irradiated samples was kept different depending on the intensity of the induced activity in order to keep the dead time of counting less than 10%. The geometry dependent efficiency curves for the γ rays of different energies and for various source-detector distances were plotted using the ORIGIN graphics software. Experimental geometry dependent efficiency data is found to be best fitted with a polynomial of
degree 5, having the following form,

\[ G \varepsilon = a_0 + a_1 X + a_2 X^2 + a_3 X^3 + a_4 X^4 + a_5 X^5 \] (11)

where, \( X \) being the energy of the characteristic \( \gamma \) ray and \( a_0, a_1, a_2, a_3, a_4, a_5 \) being the coefficients having different values for different source-detector distance. Typical geometry dependent efficiency curves as a function of \( \gamma \) ray energy are shown in Figs. 2.6.1.

The residual nuclei trapped in samples as well as Al-catcher foils were identified by their characteristic \( \gamma \) rays. Typical \( \gamma \) ray spectra of \(^{128}\text{Te}\) samples irradiated by \(^{12}\text{C}\) beam at 82.0 MeV is shown in Fig 2.6.2. Similarly, the observed \( \gamma \) rays spectra for \(^{16}\text{O}+^{159}\text{ Tb}\) system at 95 MeV and for \(^{16}\text{O}+^{169}\text{Tm}\) system at 92 MeV are shown in Figs. 2.6.3 and 2.6.4, respectively. Various peaks in the spectra correspond to different residues produced via different reaction channels. The \( \gamma \)-ray energy of some prominent peaks are indicated in these spectra.
Fig. 2.6.1 Typical geometry dependent efficiency curves for various source detector distances as a function of γ ray energy
Fig. 2.6.2: A typical γ-ray spectrum of 189Te sample irradiated by 12C beam at 82 MeV
Fig 2.6.3 A observed γ-ray spectrum for $^{16}O+^{159}Yb$ system at 95 MeV
Fig 2.6.4 A observed γ-ray spectrum for $^{16}O + ^{169}Tm$ system at 92 MeV
2.7 Recoil range distributions

In the present work, the recoil range distribution (RRD) for various radioactive residues produced in the interaction of \(^{16}O\) beam with \(^{169}Tm\) target nucleus have been measured at 86.6 MeV. The typical arrangement of target catcher assembly is shown in Fig.2.7. In the irradiation chamber the target was mounted with Al-backing facing the beam so that the catcher stack immediately followed the Thulium layer. The beam energy incident on front Al surface was 92 MeV. After an energy loss of \(\approx 5\) MeV in the Al thickness the incident beam energy was reduced to 86.6 MeV on the Tm material. A stack of 19 thin Al-catchers of thickness varying from \(\approx 16-45\ \mu g/cm^2\) was used to trap the recoiling nuclei.

Fig.2.7 The typical arrangement of target catcher assembly used for recoil range measurements.
The catcher-thicknesses used in the present experiment are given in Table 2.7.

**Table 2.7 Catcher thicknesses used for RRD**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Thickness in $\mu g/cm^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.8</td>
</tr>
<tr>
<td>2</td>
<td>19.6</td>
</tr>
<tr>
<td>3</td>
<td>27.4</td>
</tr>
<tr>
<td>4</td>
<td>27.8</td>
</tr>
<tr>
<td>5</td>
<td>28.6</td>
</tr>
<tr>
<td>6</td>
<td>29.5</td>
</tr>
<tr>
<td>7</td>
<td>30.2</td>
</tr>
<tr>
<td>8</td>
<td>30.6</td>
</tr>
<tr>
<td>9</td>
<td>31.3</td>
</tr>
<tr>
<td>10</td>
<td>31.9</td>
</tr>
<tr>
<td>12</td>
<td>32.1</td>
</tr>
<tr>
<td>13</td>
<td>33.2</td>
</tr>
<tr>
<td>14</td>
<td>33.9</td>
</tr>
<tr>
<td>15</td>
<td>37.1</td>
</tr>
<tr>
<td>16</td>
<td>39.9</td>
</tr>
<tr>
<td>17</td>
<td>44.2</td>
</tr>
<tr>
<td>18</td>
<td>46.1</td>
</tr>
<tr>
<td>19</td>
<td>47.0</td>
</tr>
</tbody>
</table>
The duration of irradiation was about 18 hrs with a beam fluence of \( \approx 3500 \mu \text{C} \). Thin \(^{169}\text{Tm}\) target of thickness \( \approx 300 \mu \text{g/cm}^2 \) was used. Both, the targets and the catchers were prepared by vacuum evaporation technique (discussed in section 2.2). The thicknesses of samples and catchers were measured prior to their use, by measuring the energy loss suffered in the foil by 5.485 MeV \( \alpha \) particles from \(^{241}\text{Am}\) source. Stopping power tables of Northcliffe and Schilling [4] were used for determining the thickness from the energy loss measurements. The activities induced in each thin catcher were followed off-line for about two weeks using a precalibrated high resolution (2 keV for 1.33 MeV \( \gamma \) ray of \(^{60}\text{Co}\)) HPGe detector of 100 c.c. active volume of CANBERRA coupled to CAMAC based software FREEDOM[9] at NSC, New Delhi. The same software was used for analyzing the data.

The experimentally measured cross-sections (\( \sigma \)) for a particular reaction products in different catcher foils were obtained using equation 4. In order to obtain the yield distribution as a function of cumulative depth in the catcher stack, the yield in each catcher was divided by its measured thickness. The resulting yield has been plotted against cumulative catcher thickness to obtain the differential recoil range distributions. Measured recoil range distributions for various residues are presented and discussed in Chapters III and V of the thesis.
2.8 Experimental uncertainties

Critical evaluation of uncertainties that are likely to introduce error in the measured excitation functions reflects the quality of measurements. Following factors may introduce errors in the present measurements.

1. Non-uniform thickness of the target material and an inaccurate estimate of foil thickness may lead to the uncertainty in the determination of the number of target nuclei. This in turn will introduce error in the measured excitation functions. To check the uniformity of the samples, the thickness of the samples were measured at different positions by α-transmission method. The thicknesses so determined were found to agree within 1%.

2. Fluctuation in the beam current may result in the variation of incident flux. The beam current was continuously monitored and any accidental stop of beam or appreciable fluctuation of the beam intensity was recorded and taken care of while calculating the total irradiation time and average beam current.

3. Dead time of counting is likely to introduce error in determining the count rates. In the present work, dead time was kept < 10% by suitably adjusting the sample detector distance.

4. Uncertainty in the fitting of the efficiency curve (< 3%) and also the solid angle effect (< 2%) [10] may lead to inaccuracy in the measurement of detector efficiency. The measured efficiency may be inaccurate on account of the statistical errors of counting of the standard source. These were minimized by accumulating the data for a longer time (≈ 3000 sec).
statistical fluctuation in efficiency is estimated to be < 2%.

5. Losses due to the nuclei recoiling out of the target may introduce error in the measured excitation functions. These were minimized by counting together the activity induced in the sample and the catcher foils, which were kept just behind the target.

6. Error in the incident beam energy has been determined by calculating the energy spread in half thickness of the sample with the help of stopping power tables of Northcliffe and Schilling [4].

These errors exclude the uncertainty of the nuclear data like branching ratio, decay constant etc., which have been taken from the Table of Isotopes [11].

The measurements done in the present studies are described in detail case wise in the next chapter for each reaction.
References


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

Chapter III
Measurements

With a view to study the complete fusion (CF) and incomplete fusion (ICF) in nuclear reactions induced by $^{12}C$ and $^{16}O$ beams, several experiments have been carried out for measuring the excitation functions (EFs) in a wide energy range. In Table 3.1, are listed the systems studied for EF measurements. The energy range covered in these systems is also indicated in this table.

Table 3.1.

<table>
<thead>
<tr>
<th>Systems studied</th>
<th>Energy range</th>
<th>Coulomb barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}C + ^{128}Te \rightarrow ^{140}Ce$</td>
<td>$\approx 42-82$ MeV</td>
<td>$\approx 42$ MeV</td>
</tr>
<tr>
<td>$^{16}O + ^{159}Tb \rightarrow ^{175}Ta$</td>
<td>$\approx 68-95$ MeV</td>
<td>$\approx 65$ MeV</td>
</tr>
<tr>
<td>$^{16}O + ^{169}Tm \rightarrow ^{185}Ir$</td>
<td>$\approx 71-95$ MeV</td>
<td>$\approx 68$ MeV</td>
</tr>
</tbody>
</table>

The excitation functions for the reactions

$^{128}Te(^{12}C,3n)^{137}mCe$, $^{128}Te(^{12}C,5n)^{135}Ce$, $^{128}Te(^{12}C,p4n)^{135}La$, $^{128}Te(^{12}C,5n)^{131}Ba$, $^{128}Te(^{12}C,\alpha n)^{131}Te$, $^{159}Tb(^{16}O,3n)^{172}Ta$, $^{159}Tb(^{16}O,4n)^{171}Ta$, $^{159}Tb(^{16}O,p3n)^{171}Lu$, $^{159}Tb(^{16}O,\alpha n)^{170}Lu$, $^{159}Tb(^{16}O,\alpha 2n)^{169}Hf$, $^{159}Tb(^{16}O,\alpha 2n)^{165}Tm$, $^{169}Tm(^{16}O,3n)^{182}Ir$, $^{169}Tm(^{16}O,4n)^{181}Ir$, $^{169}Tm(^{16}O,p2n)^{182}Os$, $^{169}Tm(^{16}O,3\alpha n)^{178}Re$, $^{169}Tm(^{16}O,2\alpha pn)^{175}Hf$ and $^{169}Tm(^{16}O,3\alpha n)^{172}Lu$ have been measured us-
ing the activation technique. Further, the recoil range distributions (RRDs) of residues produced in the $^{16}O + ^{169} Tm$ system have also been measured at 86.6 MeV in order to separate out the relative contributions of CF and ICF. To the best of our knowledge the presently measured EFs as well as RRDs are being reported for the first time. The radioactive properties of the residual nuclei viz., identified $\gamma$ rays and their branching ratios are given in tabular form in this chapter for the systems studied. Description of the different systems and individual reactions are discussed in the following[1].

3.1. $^{12}C + ^{52} Te$ SYSTEM

Table 3.1.1 Reactions, identified $\gamma$-rays and their branching ratios.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Reaction</th>
<th>$E_\gamma$(keV)</th>
<th>Abundance(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$^{128}Te(^{12}C,3n)^{137}Ce$</td>
<td>254.29</td>
<td>11.0</td>
</tr>
<tr>
<td>2.</td>
<td>$^{128}Te(^{12}C,5n)^{135}Ce$</td>
<td>206.51, 265.55</td>
<td>7.85, 42.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>300.06, 518.05</td>
<td>22.70, 13.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>572.26, 606.77</td>
<td>10.50, 19.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>783.61, 828.38</td>
<td>10.50, 5.18</td>
</tr>
<tr>
<td>3.</td>
<td>$^{128}Te(^{12}C,p4n)^{135}La$</td>
<td>480.54</td>
<td>1.54</td>
</tr>
<tr>
<td>4.</td>
<td>$^{128}Te(^{12}C,a3n)^{133m}Ba$</td>
<td>276.09</td>
<td>17.7</td>
</tr>
<tr>
<td>5.</td>
<td>$^{128}Te(^{12}C,a5n)^{131}Ba$</td>
<td>123.78, 216.05</td>
<td>29.10, 20.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>373.19, 496.25</td>
<td>13.30, 44.0</td>
</tr>
<tr>
<td>6.</td>
<td>$^{128}Te(^{12}C,a4pn)^{131m}Te$</td>
<td>149.72</td>
<td>5.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200.63, 240.93</td>
<td>7.54, 7.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>334.27, 773.67</td>
<td>9.55, 38.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>793.77, 852.24</td>
<td>13.8, 20.6</td>
</tr>
</tbody>
</table>
1. $^{128}\text{Te}^{(12C,3n)}$ channel [$residue =^{137m}_{58}\text{Ce}, t_{1/2}=1.4\text{ d}, J^\pi = 11/2^-$]

The reaction $^{128}\text{Te}^{(12C,3n)}$ produces residual isotope $^{137}\text{Ce}$ which has both the ground ($t_{1/2}=9\text{ h}$) as well as metastable states ($t_{1/2}=1.4\text{ d}$). The metastable state $^{137m}\text{Ce}$ decays to ground state by the emission of 254.2 keV $\gamma$-ray. Since, $^{137}\text{Ce}$ ($t_{1/2}=9.0\text{ h}$) decay by EC/$\beta^+$ emitting $\gamma$-rays of very low intensities, it could not be observed. As such, contribution of only metastable state $^{137m}\text{Ce}$ has been measured.

2. $^{128}\text{Te}^{(12C,5n)}$ channel [$residue =^{135}_{58}\text{Ce}, t_{1/2}=17.8\text{ h}, J^\pi = 1/2^+$]

The residue $^{135}\text{Ce}$ is formed by the complete fusion of $^{12C}$ with $^{128}\text{Te}$ followed by the evaporation of 5 neutrons from the compound nucleus $^{140}\text{Ce}$. As a representative case the relevant portions of the decay scheme for the residual radioactive isotope $^{135}\text{Ce}$ produced in this reaction is shown in Fig.3.1[3]. Energies given in the decay scheme are in keV. Levels are represented by horizontal bars and the transitions by vertical arrows. Heavy bar denote ground state. The $\gamma$ ray transitions to a given final level are represented by an arrow with solid circles as the "tails" beneath each level which decays to the final level.

3. $^{128}\text{Te}^{(12C,p4n)}$ channel [$residue =^{135}_{57}\text{La}, t_{1/2}=19.5\text{ h}, J^\pi = 5/2^+$]

The residue $^{135}\text{La}$ is formed by the complete fusion of $^{12C}$ with $^{128}\text{Te}$ followed by the evaporation of a proton and 4 neutrons from the compound nucleus $^{140}\text{Ce}$. Further, the residue $^{135}\text{La}$ may be produced independently via the reaction $(^{12C,p4n})$ and the same residue ($^{135}\text{La}$) may also be pro-
Fig. 3.1 Partial decay scheme for $^{135}_{57}$Ce
duced by $\beta^+$ decay of its higher charge isobar precursor ($^{135}\text{Ce}$) produced via $^{128}\text{Te}(^{12}\text{C},5n)$ reaction. The independent yield of $^{135}\text{La}$ could not be measured in the present analysis because the half-lives of the residue $^{135}\text{La}$ and its precursor $^{135}\text{Ce}$ are not very much different (19.5 h and 17.8 h respectively). However, in such cases, formulations developed in reference [2] may be followed, according to which the ratio of the activities of the parent ($^{135}\text{Ce}$) to the daughter ($^{135}\text{La}$) having nearly same half-lives would increase linearly for some time. Using these formulations, the yield of $^{135}\text{La}$ via the precursor decay of $^{135}\text{Ce}$ has been found to be less than 1 mb at 82 MeV.

The presently measured cross-sections for Ce and La isotopes produced via complete fusion in the $^{12}\text{C}+^{128}\text{Te}$ system are tabulated in Table 3.1.2

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma(^{137m}\text{Ce})$ (mb)</th>
<th>$\sigma(^{135}\text{Ce})$ (mb)</th>
<th>$\sigma(^{135}\text{La})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.2±1.4</td>
<td>14.4±1.7</td>
<td>1.7±0.7</td>
<td>4.4±0.4</td>
</tr>
<tr>
<td>57.7±1.2</td>
<td>114.3±13.4</td>
<td>2.2±0.6</td>
<td>1.5±0.1</td>
</tr>
<tr>
<td>71.0±1.0</td>
<td>18.2±2.3</td>
<td>308.2±22.9</td>
<td>56.1±6.2</td>
</tr>
<tr>
<td>81.7±0.4</td>
<td>8.9±1.3</td>
<td>292.7±32.1</td>
<td>82.4±9.1</td>
</tr>
</tbody>
</table>

4. $^{128}\text{Te}(^{12}C,\alpha 3n)$ channel [$\text{residue} = {}^{133m}_{56}\text{Ba}, t_{1/2}=1.6 \text{ d}, J^\pi = 11/2^-$]

The isotope $^{133m}_{56}\text{Ba}$ may be formed either by the complete fusion of $^{12}C$ with $^{128}\text{Te}$ forming compound system $^{140}\text{Ce}$ followed by the evaporation of an $\alpha$ particle and 3 neutrons and/or by the incomplete fusion of $^8\text{Be}$ fragment (if
$^{12}C$ undergoes breakup into $\alpha$ and $^8Be$ fragments) followed by the emission of 3 neutrons. The measured cross-sections for the residue $^{133m}Ba$ may contain the contributions from both the CF as well as ICF channels. It may be pointed out that the ground state $^{56}_{\text{Ba}}$ could not be observed due to its very long half-life (10.54 years).

5. $^{128}Te(^{12}C, \alpha5n)$ channel [$residue =^{131}_{56}Ba, \ t_{1/2}=11.8 \ d, \ J^\pi = 1/2^+$]

The $^{131}_{56}Ba$ isotope may be formed either by the complete fusion of $^{12}C$ with $^{128}Te$ followed by the evaporation of an $\alpha$ particle and 5 neutrons and/or by the incomplete fusion of $^8Be$ fragment (if $^{12}C$ undergoes breakup into $\alpha$ and $^8Be$ fragments) followed by the emission of 5 neutrons. It may again be pointed out that the measured activity of residual nucleus $^{131}_{56}Ba$ may have both CF and ICF contributions.

6. $^{128}Te(^{12}C, \alpha4pn)$ channel [$residue =^{131m}_{52}Te, \ t_{1/2}= 1.2 \ d, \ J^\pi = 11/2^-$]

The $^{131m}_{52}Te$ isotope may be produced either by the complete fusion of $^{12}C$ with $^{128}Te$ followed by the evaporation of an $\alpha$ particle, 4 protons and a neutron and/or by the incomplete fusion of $^8Be$ fragment (if $^{12}C$ undergoes breakup into $\alpha$ and $^8Be$ fragments) followed by the emission of 4 protons and a neutron. The reaction $^{128}Te(^{12}C, \alpha4pn)$ produces both the ground state $^{131}Te (t_{1/2}= 25 \ min)$ as well as isomeric state $^{131m}Te(t_{1/2}= 1.2d)$. The isomeric state decays to ground state. Since, the counting of the irradiated samples was started after considerable delay due to the high activity of the samples, the ground state contribution could not be separated in this
It may, however, be pointed out that the residual nucleus $^{131m}Te$ produced in this reaction may also be populated via deep inelastic collision in addition to fusion, since $^{128}Te$ target (enrichment $\approx 87\%$) may contain $^{130}Te$ as contamination. However, the relative abundance of $^{130}Te$ is expected to be $\approx 6\%$ in the sample. Since deep inelastic collision is likely to dominate at higher incident energies, the contribution from deep inelastic collision is expected to be very low.

The presently measured cross-sections for Ba and Te isotopes are tabulated in Table 3.1.3.

**Table 3.1.3 Measured cross-sections for Ba and Te isotopes.**

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma(^{133}Ba)$ (mb)</th>
<th>$\sigma(^{131}Ba)$ (mb)</th>
<th>$\sigma(^{131m}Te)$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>42.2±1.4</td>
<td>0.8±0.1</td>
<td>-</td>
<td>4.4±0.5</td>
</tr>
<tr>
<td>57.7±1.2</td>
<td>7.8±0.8</td>
<td>-</td>
<td>4.9±0.5</td>
</tr>
<tr>
<td>71.0±1.0</td>
<td>43.6±4.8</td>
<td>0.73±0.07</td>
<td>22.2±2.5</td>
</tr>
<tr>
<td>80.0±0.9</td>
<td>37.6±4.2</td>
<td>7.1±0.8</td>
<td>30.9±3.5</td>
</tr>
</tbody>
</table>
### 3.2 \( ^{16}O + ^{159}Tb \) SYSTEM

Table 3.2.1 List of reactions, identified \( \gamma \)-rays and their branching ratios.

<table>
<thead>
<tr>
<th>S. No</th>
<th>Reaction</th>
<th>( E_\gamma (\text{keV}) )</th>
<th>Abundance(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( ^{159}Tb(^{16}O, 3n)^{172}Ta )</td>
<td>213.9, 318.7</td>
<td>52, 4.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1085.5, 1109.2</td>
<td>7.6, 14</td>
</tr>
<tr>
<td>2.</td>
<td>( ^{159}Tb(^{16}O, 4n)^{171}Ta )</td>
<td>152.2, 166.1</td>
<td>5.8(^a), 19.2(^a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>175.1, 444.1, 501.3, 506.1</td>
<td>16(^a), 15.6(^a), 15.6(^a), 54(^a)</td>
</tr>
<tr>
<td>3.</td>
<td>( ^{159}Tb(^{16}O, 5n)^{170}Ta )</td>
<td>860.4</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>986.9, 987.0</td>
<td>3.3, 5.88</td>
</tr>
<tr>
<td>4.</td>
<td>( ^{159}Tb(^{16}O, p3n)^{171}Hf )</td>
<td>122.0, 137.6</td>
<td>120(^a), 51(^a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>147.0, 295.6</td>
<td>16.2(^a), 52(^a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>347.1, 469.2</td>
<td>56 (^a), 38(^a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>662.2, 1071.8</td>
<td>100(^a), 56(^a)</td>
</tr>
<tr>
<td>5.</td>
<td>( ^{159}Tb(^{16}O, p4n)^{170}Hf )</td>
<td>120.1, 164.6, 620.6</td>
<td>19.0, 33, 23</td>
</tr>
<tr>
<td>6.</td>
<td>( ^{159}Tb(^{16}O, 2p2n)^{171}Lu )</td>
<td>667.0, 739.8, 780.7</td>
<td>11.0, 48.1, 4.3</td>
</tr>
<tr>
<td>7.</td>
<td>( ^{159}Tb(^{16}O, \alpha n)^{170}Lu )</td>
<td>193.1</td>
<td>2.07</td>
</tr>
<tr>
<td>8.</td>
<td>( ^{159}Tb(^{16}O, \alpha 2n)^{169}Lu )</td>
<td>191.2</td>
<td>20.7</td>
</tr>
<tr>
<td>9.</td>
<td>( ^{159}Tb(^{16}O, 2\alpha 2n)^{165}Tm )</td>
<td>242.8, 296.0</td>
<td>35, 23</td>
</tr>
</tbody>
</table>

\(^a\) relative abundance of characteristic \( \gamma \) lines.
1. $^{159}Tb(^{16}O, 3n)$ channel $[\text{residue} = ^{172}Ta, t_{1/2} = 36.8 \text{ m}, J^\pi = 3^-]$

The evaporation residue $^{172}Ta$ is formed by the complete fusion of $^{16}O$ with $^{159}Tb$ forming the compound system $^{175}Ta$ followed by the emission of 3 neutrons.

2. $^{159}Tb(^{16}O, 4n)$ channel $[\text{residue} = ^{171}Ta, t_{1/2} = 23.3 \text{ m}, J^\pi = 5/2^-]$

The residue $^{171}Ta$ is formed by the complete fusion of $^{16}O$ with $^{159}Tb$ followed by the evaporation of 4 neutrons from the compound nucleus $^{175}Ta$. It may be noted that the measured cross-sections for this reaction are given (Table 3.2.2) as relative, since the absolute intensities of the $\gamma$-rays for the residue $^{171}Ta$ are not known, only relative intensities are given in reference [3].

3. $^{159}Tb(^{16}O, 5n)$ channel $[\text{residue} = ^{170}Ta, t_{1/2} = 6.76 \text{ m}, J^\pi = 3^+]$

The evaporation residue $^{170}Ta$ is formed by the complete fusion of $^{16}O$ with $^{159}Tb$ forming the compound system $^{175}Ta$ followed by the emission of 5 neutrons.

The presently measured cross-sections for $Ta$ isotopes produced via complete fusion in the $^{16}O + ^{159}Tb$ system are tabulated in Table 3.2.2.
Table 3.2.2 Measured cross-sections for Ta isotopes

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma^{(172)Ta}$ (mb)</th>
<th>$\sigma^{(171)Ta}$ relative (mb)</th>
<th>$\sigma^{(170)Ta}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>69.3±1.0</td>
<td>0.34 ±0.08</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>75.2±0.9</td>
<td>19.8±3.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>78.7±0.9</td>
<td>34.28±4.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>83.2±0.9</td>
<td>48.14±5.1</td>
<td>72.02±9.4</td>
<td>64.91±9.4</td>
</tr>
<tr>
<td>87.2±0.8</td>
<td>12.65±2.2</td>
<td>50.48±6.0</td>
<td>100.27±15.4</td>
</tr>
<tr>
<td>89.6±0.4</td>
<td>11.89±2.4</td>
<td>59.91±6.1</td>
<td>363.48±41.3</td>
</tr>
<tr>
<td>94.6±0.4</td>
<td>8.53±1.5</td>
<td>22.65±2.5</td>
<td>390.19±44.7</td>
</tr>
</tbody>
</table>

4. $^{159}Tb^{(16}O,p3n)$ channel [$residue =^{171}_{72}Hf$, $t_{1/2} = 12.1$ h, $J^* = 7/2^+$]

The residue $^{171}Hf$ is formed by the complete fusion of $^{16}O$ with $^{159}Tb$ followed by the evaporation of a proton and 3 neutrons from the compound nucleus $^{175}Ta$. The same residue ($^{171}Hf$) may also be produced by the electron capture (EC) and/or $\beta^+$ decay of the higher charge precursor isobar $^{73}_{71}Ta$ produced via reaction $^{165}Tb^{(O,4n)}$. The cumulative cross-section of $^{171}Hf$ has been measured by following the activities at times longer than about 8-10 half lives of the precursor, so that precursor completely decays to the $^{171}Hf$. Using the formulations of Cavinato et. al.,[4] described in Chapter II, the independent cross sections for the production of $^{171}Hf$ via reaction $^{165}Tb^{(O,p3n)}$ have been determined at different energies. Using the formulations of Cavinato et. al.,[4] given in Chapter II, the equation for separating the independent yield $\sigma_{ind}^{(171}Hf)$ from the cumulative yield $\sigma_{cum}^{(171}Hf)$,
due to the contribution from the precursor ($^{171}Ta$) decay has been obtained as,

$$\sigma_{\text{cum}}^{171}Hf = \sigma_{\text{ind}}^{171}Hf + 1.03315\sigma^{171}Ta \quad (1)$$

The above equation has been used for separating the independent contributions from the cumulative yield. The cumulative and independent yields so obtained are given in Table 3.2.3. It may however be pointed out that the intensities of $\gamma$-rays from $^{171}Hf$ are relative, as such cross-sections are relative as given in Table 3.2.3.

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma_{\text{cum}}^{171}Hf$ rel (mb)</th>
<th>$\sigma_{\text{ind}}^{171}Hf$ rel (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.7±0.9</td>
<td>5.7±0.63</td>
<td>-</td>
</tr>
<tr>
<td>83.2±0.9</td>
<td>107.38±32.9</td>
<td>32.97±9.4</td>
</tr>
<tr>
<td>87.2±0.8</td>
<td>65.43±13.2</td>
<td>13.28±6.0</td>
</tr>
<tr>
<td>89.6±0.4</td>
<td>72.32±10.4</td>
<td>10.42±6.1</td>
</tr>
<tr>
<td>96.6±0.4</td>
<td>27.59±4.2</td>
<td>4.15±2.5</td>
</tr>
</tbody>
</table>

5. $^{159}Tb(16O,p4n)$ channel [$\text{residue} = ^{170}_{170}Hf, t_{1/2} = 16 \text{ h}, J^\pi = 0^+$]

The residue $^{170}Hf$ may be formed by the complete fusion of $^{16}O$ with $^{159}Tb$ followed by the emission of a proton and 4 neutrons from the compound nucleus $^{175}Ta$. The same residue ($^{170}Hf$) may also be produced by
the electron capture (EC) and/or \( \beta^+ \) decay of the higher charge precursor isobar \( ^{73}Ta \) produced via reaction \( ^{159}Tb(^{16}O,5n) \). The cumulative cross-section of \( ^{170}Hf \) has been measured by following the activities at considerably longer times, so that precursor completely decays to the \( ^{170}Hf \). The independent cross section for the production of \( ^{170}Hf \) has been separated by using the following expression;

\[
\sigma_{cum}^{^{170}Hf} = \sigma_{ind}^{^{170}Hf} + 1.007087\sigma^{^{170}Ta}
\]

(2)

The cumulative as well as independent yields thus obtained are given in Table 3.2.4.

**Table 3.2.4** Cumulative and Independent yields for \( ^{170}Hf \) isotope.

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>( \sigma_{cum}^{^{170}Hf} ) (mb)</th>
<th>( \sigma_{ind}^{^{170}Hf} ) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>83.2±0.9</td>
<td>84.65±10.0</td>
<td>19.23±3.2</td>
</tr>
<tr>
<td>87.2±0.9</td>
<td>177.32±19.5</td>
<td>76.34±10.8</td>
</tr>
<tr>
<td>89.6±0.4</td>
<td>574.32±68.8</td>
<td>208.26±26.0</td>
</tr>
<tr>
<td>94.6±0.4</td>
<td>427.83±55.0</td>
<td>34.88±6.5</td>
</tr>
</tbody>
</table>

6. \( ^{159}Ta(^{16}O,2p2n) \) channel \([\text{residue} = ^{171}Lu, t_{1/2} = 8.24 \text{ d } J^\pi = 7/2^+]\)

The residue \( ^{171}Lu \) may be formed by the complete fusion of \( ^{16}O \) with \( ^{159}Tb \) followed by emission of two protons and two neutrons or an \( \alpha \) particle from the compound nucleus \( ^{179}Ta \). The same residue \( ^{171}Lu \) may also be produced
by the fusion of $^{12}\text{C}$ fragment (if $^{16}\text{O}$ undergoes breakup into $\alpha$ and $^{12}\text{C}$ fragments) leaving the residue $^{171}\text{Lu}$ in excited state. The measured cross sections include contributions from both the complete as well as incomplete fusion processes. The same residue may also be produced by the electron capture (EC) and/or $\beta^+$ decay of the higher charge precursor isobars $^{171}\text{Ta}$ and $^{172}\text{Hf}$ produced via reactions $^{159}\text{Tb}(O,5n)$ and $^{159}\text{Tb}(O,p4n)$, respectively. The cumulative cross-section of $^{171}\text{Lu}$ has been measured by following the activities at times considerably longer, so that precursors completely decays to the $^{171}\text{Lu}$. It may, however, be pointed out that one of precursors $^{171}\text{Hf}$ of the residue $^{171}\text{Lu}$ may also have precursor decay contribution from $^{171}\text{Ta}$. Since, the cross-sections of precursors (i.e.,$^{171}\text{Ta}$ and $^{171}\text{Hf}$) of the residue $^{171}\text{Lu}$ have been measured as relative and hence, independent yield of the production of $^{171}\text{Lu}$ isotope could not be separated and only cumulative yields are given in Table 3.2.5. The measured cross-sections for the residue $^{171}\text{Lu}$ may have contribution from both CF as well as ICF channels.

7. $^{159}\text{Tb}(^{16}\text{O},\alpha n)$ channel [$\text{residue =}^{170}\text{Lu} , t_{l/2}=2\text{ d } J^\pi = 0^+\text{]}$

The residue $^{170}\text{Lu}$ may be formed by the complete fusion of $^{16}\text{O}$ with $^{159}\text{Tb}$ followed by emission of an $\alpha$ particle and a neutron from the compound nucleus $^{175}\text{Ta}$. The same residue may also be produced by the fusion of $^{12}\text{C}$ fragment (if $^{16}\text{O}$ undergoes breakup into $\alpha$ and $^{12}\text{C}$ fragments) followed by the emission of a neutron. The measured cross sections may have contributions from both the complete as well as incomplete fusion processes.
8. $^{159}\text{Tb}(^{16}\text{O}, \alpha 2\text{n})$ channel \(\text{[residue }= ^{169}\text{Lu, } t_{1/2}= 34 \text{ h } J^\pi = 7/2^+\)]

The residue $^{169}\text{Lu}$ may be produced by the complete fusion of $^{16}\text{O}$ with $^{159}\text{Tb}$ followed by emission of an $\alpha$ particle and two neutrons from the compound nucleus $^{175}\text{Ta}$. The same residue $^{169}\text{Lu}$ may also be produced by the incomplete fusion of $^{12}\text{C}$ fragment (if $^{16}\text{O}$ undergoes breakup into $\alpha$ and $^{12}\text{C}$ fragments) followed by the emission of two neutrons. The measured cross sections include contributions from both the complete as well as incomplete fusion processes.

9. $^{159}\text{Tb}(^{16}\text{O}, 2\alpha 2\text{n})$ channel \(\text{[residue }= ^{165}\text{Tm, } t_{1/2}= 1.25 \text{ d } J^\pi = 1/2^+\)]

The residue $^{165}\text{Tm}$ may be formed by the complete fusion of $^{16}\text{O}$ with $^{159}\text{Tb}$ followed by emission of two $\alpha$-particles and two neutrons from the compound nucleus $^{175}\text{Ta}$. The same residue $^{165}\text{Tm}$ may also be produced by the fusion of $^8\text{Be}$ fragment (if $^{16}\text{O}$ undergoes breakup into $2\alpha$-particles and a $^8\text{Be}$ fragments) followed by the emission of two neutron. The measured cross sections include contributions from both the complete as well as incomplete fusion processes.

The measured cross-sections for $\text{Lu}$ and $\text{Tm}$ isotopes produced via complete as well as incomplete fusion in the $^{16}\text{O}+^{159}\text{Tb}$ system are listed in Table 3.2.5
Table 3.2.5 Measured cross-section for \(Lu\) and \(Tm\) isotopes.

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>(\sigma^{(171) Lu}) (mb)</th>
<th>(\sigma^{(170) Lu}) (mb)</th>
<th>(\sigma^{(169) Lu}) mb</th>
<th>(\sigma^{(165) Tm}) mb</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.7±0.9</td>
<td>29.54±3.1</td>
<td>-</td>
<td>4.24±0.5</td>
<td>-</td>
</tr>
<tr>
<td>83.2±0.9</td>
<td>61.63±6.5</td>
<td>6.54±1.5</td>
<td>76.84±11.2</td>
<td>5.53±0.6</td>
</tr>
<tr>
<td>87.2±0.8</td>
<td>1667.62±170.6</td>
<td>8.8±1.6</td>
<td>43.48±4.5</td>
<td>7.54±0.8</td>
</tr>
<tr>
<td>89.6±0.4</td>
<td>611.80±64.0</td>
<td>49.81±6.7</td>
<td>80.65±9.4</td>
<td>10.36±1.3</td>
</tr>
<tr>
<td>94.6±0.4</td>
<td>255.89±26.3</td>
<td>31.33±5.4</td>
<td>34.49±4.5</td>
<td>5.76±1.1</td>
</tr>
</tbody>
</table>
### 3.3 $^{16}_8\text{O} + ^{169}_{69}\text{Tm}$ SYSTEM

Table 3.3.1. List of reactions, identified $\gamma$-rays and their branching ratios.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Reaction</th>
<th>$E_\gamma$(keV)</th>
<th>Abundance(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$^{169}\text{Tm}(^{16}_8\text{O},3n)^{182}\text{Ir}$</td>
<td>126.9, 273.09, 764.15, 891.07, 912.22</td>
<td>34.4, 43, 5.6, 5.7, 8.7</td>
</tr>
<tr>
<td>2.</td>
<td>$^{169}\text{Tm}(^{16}_8\text{O},4n)^{181}\text{Ir}$</td>
<td>107.6, 123.5, 184.6, 227.0, 231.6, 318.9</td>
<td>100a, 28a, 28a, 58a, 30a, 46a</td>
</tr>
<tr>
<td>3.</td>
<td>$^{169}\text{Tm}(^{16}_8\text{O},p2n)^{182}\text{Os}$</td>
<td>180.22, 263.29</td>
<td>34.7, 6.6</td>
</tr>
<tr>
<td>4.</td>
<td>$^{169}\text{Tm}(^{16}_8\text{O},p3n)^{181}\text{Os}$</td>
<td>238.68, 826.74</td>
<td>44, 20.2</td>
</tr>
<tr>
<td>5.</td>
<td>$^{169}\text{Tm}(^{16}_8\text{O},\alpha)^{181}\text{Re}$</td>
<td>360.7, 365.59</td>
<td>20, 57.0</td>
</tr>
<tr>
<td>6.</td>
<td>$^{169}\text{Tm}(^{16}_8\text{O},\alpha3n)^{178}\text{Re}$</td>
<td>237.19</td>
<td>45</td>
</tr>
<tr>
<td>7.</td>
<td>$^{169}\text{Tm}(^{16}_8\text{O},2apn)^{175}\text{Hf}$</td>
<td>343.4</td>
<td>87</td>
</tr>
<tr>
<td>8.</td>
<td>$^{169}\text{Tm}(^{16}_8\text{O},3an)^{172}\text{Lu}$</td>
<td>1093.6</td>
<td>63.5</td>
</tr>
</tbody>
</table>

(a relative abundance of characteristic $\gamma$ lines.)
1. $^{169}\text{Tm}(^{16}O, 3n)$ channel [$residue = ^{182}_{77}\text{Ir}, t_{1/2} = 15 \text{ m}$]

The residue $^{182}\text{Ir}$ is formed by the complete fusion of $^{16}O$ with $^{169}\text{Tm}$ forming the compound system $^{185}_{77}\text{Ir}$ followed by the evaporation of 3 neutrons.

2. $^{169}\text{Tm}(^{16}O, 4n)$ channel [$residue = ^{181}_{77}\text{Ir}, t_{1/2} = 4.9 \text{ m}, J^\pi = 7/2^+$]

The residue $^{181}\text{Ir}$ is formed by the complete fusion of $^{16}O$ with $^{169}\text{Tm}$ followed by the evaporation of 4 neutrons from the compound nucleus $^{185}\text{Ir}$. It may be noted that the measured cross-sections for this reaction are given in Table 3.3.2 as relative, since the absolute intensities of the $\gamma$-rays for the residue $^{181}\text{Ir}$ are not known, only relative intensities are given in reference [3].

The presently measured cross-sections for $\text{Ir}$ isotopes produced via complete fusion in the $^{16}O+^{169}\text{Tm}$ system are tabulated in Table 3.3.2
Table 3.3.2 Measured cross-sections for $^{191}$Ir isotopes

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma(^{182}$Ir) (mb)</th>
<th>$\sigma(^{181}$Ir) relative (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.7±1.0</td>
<td>3.28±0.7</td>
<td>-</td>
</tr>
<tr>
<td>74.9±0.9</td>
<td>42.30±7.2</td>
<td>3.44±1.5</td>
</tr>
<tr>
<td>78.7±0.9</td>
<td>59.86±13.9</td>
<td>16.72±2.3</td>
</tr>
<tr>
<td>82.0±0.8</td>
<td>86.43±14.8</td>
<td>26.12±4.3</td>
</tr>
<tr>
<td>85.8±0.8</td>
<td>47.64±7.7</td>
<td>38.06±9.5</td>
</tr>
<tr>
<td>88.9±1.0</td>
<td>35.23±3.9</td>
<td>48.53±5.1</td>
</tr>
<tr>
<td>91.6±0.4</td>
<td>13.77±3.15</td>
<td>35.03±5.5</td>
</tr>
<tr>
<td>94.6±0.4</td>
<td>8.47±1.4</td>
<td>28.12±3.8</td>
</tr>
</tbody>
</table>

3. $^{169}$Tm($^{16}$O, p2n) channel [residue = $^{182}$Os, $t_{1/2}$ = 21.6 h, $J^\pi = 0^+$]

The residue $^{182}$Os is formed by the complete fusion of $^{16}$O with $^{169}$Tm followed by the evaporation of a proton and 2 neutrons from the compound nucleus $^{185}$Ir. The same residue $^{182}$Os may also be produced by the electron capture (EC) and/or $\beta^+$ decay of the higher charge precursor isobar $^{182}$Ir produced via the reaction $^{169}$Tm($^{16}$O, 3n). The cumulative cross-section for the production of $^{182}$Os has been measured by following the activities at times longer than about 8-10 half lives of the precursor, so that precursor completely decays to the $^{182}$Os. The independent cross sections for the production of $^{182}$Os has been determined using the expression:

$$\sigma_{\text{cum}} = \sigma_{\text{ind}}(^{182}$Os) + 1.011709\sigma(^{182}$Ir)$$  \hspace{1cm} (3)
4. $^{169}Tm(^{16}O,p3n)$ channel \([\text{residue} =^{181}_{76} Os, \ t_{1/2}=1.75 \ h, \ J^\pi = 1/2^-]\)

The evaporation residue $^{181}Os$ is formed by evaporation of a proton and 3 neutrons from the compound nucleus $^{185}Ir$. The same residue $^{181}Os$ may also be produced by the electron capture (EC) and/or $\beta^+$ decay of the higher charge precursor $^{181}_{77}Ir$ isobar produced via the reaction $^{169}Tm(^{16}O,4n)$. The cumulative cross-section of $^{181}Os$ has been measured by following the activities at considerably longer times. In this case the independent cross section of residue $^{181}Os$ could not be separated since the cross-sections of its precursor are relative. Since, the counting was started after 10 min of the stop of irradiation, as such, the activity of metastable state of $^{181}_{76}Os$ of half life $t_{1/2} = 2.5 \ min$ could not be observed.

The measured cross-sections for $Os$ isotopes produced via complete fusion in the $^{16}O+^{169}Tm$ system are listed in Table 3.3.3.
Table 3.3.3 Measured cross-sections for Os isotopes.

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma_{\text{cum}}^{(182}\text{Os})$ (mb)</th>
<th>$\sigma_{\text{ind}}^{(182}\text{Os})$ (mb)</th>
<th>$\sigma^{(181}\text{Os})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.7±1.0</td>
<td>4.58±1.4</td>
<td>1.26±0.6</td>
<td>2.72±0.4</td>
</tr>
<tr>
<td>74.9±0.9</td>
<td>82.77±10.0</td>
<td>39.98±5.1</td>
<td>4.81±1.2</td>
</tr>
<tr>
<td>78.7±0.9</td>
<td>139.41±22.9</td>
<td>78.85±13.8</td>
<td>32.81±4.3</td>
</tr>
<tr>
<td>82.0±0.8</td>
<td>155.6±20.7</td>
<td>68.15±8.3</td>
<td>129.0±16.3</td>
</tr>
<tr>
<td>85.8±0.8</td>
<td>107.46±14.4</td>
<td>59.28±7.5</td>
<td>198.02±23.3</td>
</tr>
<tr>
<td>88.9±1.0</td>
<td>71.50±9.9</td>
<td>35.84±6.2</td>
<td>250.92±31.1</td>
</tr>
<tr>
<td>91.6±0.4</td>
<td>29.37±4.1</td>
<td>15.45±4.4</td>
<td>153.8±17.8</td>
</tr>
<tr>
<td>94.6±0.4</td>
<td>18.42±3.7</td>
<td>9.85±2.7</td>
<td>173.1±22.8</td>
</tr>
</tbody>
</table>

5. $^{169}\text{Tm}(^{16}\text{O},2p2n)$ channel [residue $=^{181}\text{Re}$, $t_{1/2}=20$ h, $J^e = 5/2^+$]

The evaporation residue $^{181}\text{Re}$ may be produced by evaporation of 2 protons and 2 neutrons or an $\alpha$ particle from the compound nucleus $^{185}\text{Ir}$. The residue $^{181}\text{Re}$ may also be populated by the electron capture (EC) and/or $\beta^+$ decay of the higher charge precursor isobars i.e., $^{181}\text{Ir}$ and $^{181}\text{Os}$ produced via reactions $^{169}\text{Tm}(^{16}\text{O},4n)$ and $^{169}\text{Tm}(^{16}\text{O},p3n)$, respectively. In the present measurements the independent cross section of residue $^{181}\text{Re}$ could not be separated because the cross-sections of one of its precursors $^{181}\text{Ir}$ are not absolute but relative, as such cumulative cross-sections for residue $^{181}\text{Re}$ are given in Table 3.3.4.
6. $^{169}Tm(^{16}O, \alpha 3n)$ channel \([\text{residue } = ^{178}_{75} \text{Re}, t_{1/2} = 13.2 \text{ m}, J^e = (3)]\)

The evaporation residue $^{181}\text{Re}$ may be formed by the complete fusion of $^{16}O$ with $^{169}Tm$ followed by emission of an $\alpha$ particle and a neutron from the compound nucleus $^{185}Ir$. The same residue may also be produced by the fusion of $^{12}C$ fragment (if $^{16}O$ undergoes breakup into $\alpha$ and $^{12}C$ fragments) followed by the emission of three neutrons. The measured cross sections include contributions from both the complete as well as incomplete fusion processes.

The experimentally measured cross-sections for $\text{Re}$ isotopes produced via complete as well as incomplete fusion in the $^{16}O+^{169}Tm$ system are listed in Table 3.3.4.

**Table 3.3.4** Cross-sections for $^{181}\text{Re}$ and $^{178}\text{Re}$ isotopes.

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma(^{181}\text{Re})$ (mb)</th>
<th>$\sigma(^{178}\text{Re})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.7±1.0</td>
<td>2.66±0.7</td>
<td>-</td>
</tr>
<tr>
<td>74.9±0.9</td>
<td>5.35±0.7</td>
<td>-</td>
</tr>
<tr>
<td>78.7±0.9</td>
<td>137.37±28.7</td>
<td>1.74±0.2</td>
</tr>
<tr>
<td>82.0±0.8</td>
<td>391.49±83.0</td>
<td>5.2±0.8</td>
</tr>
<tr>
<td>85.8±0.8</td>
<td>594.02±90.6</td>
<td>9.02±1.2</td>
</tr>
<tr>
<td>88.9±0.8</td>
<td>607.94±86.7</td>
<td>27.34±5.3</td>
</tr>
<tr>
<td>91.6±0.4</td>
<td>526.23±78.6</td>
<td>32.14±3.7</td>
</tr>
<tr>
<td>94.6±0.4</td>
<td>441.99±66.9</td>
<td>34.31±5.5</td>
</tr>
</tbody>
</table>
7. $^{169}\text{Tm}(^{16}O, 2\alpha pn)$ channel [$\text{residue}=^{175}Hf, t_{1/2}=70 \text{ d}, J^r = 5/2^-$]

The evaporation residue $^{175}Hf$ may be formed by the complete fusion of $^{16}O$ with $^{169}\text{Tm}$ followed by emission of $2\alpha$-particles, a proton and a neutron from the compound nucleus $^{185}\text{Ir}$. The same residue $^{175}Hf$ may also be produced by the fusion of $^8\text{Be}$ fragment (if $^{16}O$ undergoes breakup into $2\alpha$, and $^8\text{Be}$ fragments) followed by the emission of a proton and a neutron. The measured cross sections include contributions from both the complete fusion as well as incomplete fusion processes.

8. $^{169}\text{Tm}(^{16}O, 3\alpha n)$ channel [$\text{residue}=^{172}Lu, t_{1/2}=6.7 \text{ d}, J^r = 4^-$]

The evaporation residue $^{172}Lu$ may be formed by the complete fusion of $^{16}O$ with $^{169}\text{Tm}$ followed by emission of $3\alpha$-particles and a neutron from the compound nucleus $^{185}\text{Ir}$. The same residue $^{172}Lu$ may also be produced by the incomplete fusion of $\alpha$-particle (if $^{16}O$ undergoes breakup into $\alpha$, and $^{12}C$ fragments) followed by the emission of a neutrons. The measured cross sections include contributions from both the complete as well as incomplete fusion processes.

The measured cross-sections for $Hf$ and $Lu$ isotopes produced via complete as well as incomplete fusion in the $^{16}O+^{169}\text{Tm}$ system are listed in table 3.3.5.
Table 3.3.5 Experimentally measured cross-sections for $^{175}Hf$ and $^{172}Lu$ isotopes.

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma(^{175}Hf)$ (mb)</th>
<th>$\sigma(^{172}Lu)$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.7±0.9</td>
<td>-</td>
<td>14.93±2.1</td>
</tr>
<tr>
<td>82.0±0.8</td>
<td>-</td>
<td>20.58±2.6</td>
</tr>
<tr>
<td>85.8±0.8</td>
<td>0.57±0.1</td>
<td>31.32±3.9</td>
</tr>
<tr>
<td>88.9±0.8</td>
<td>2.53±0.4</td>
<td>30.27±3.7</td>
</tr>
<tr>
<td>91.6±0.4</td>
<td>2.96±0.5</td>
<td>28.39±3.1</td>
</tr>
<tr>
<td>94.6±0.4</td>
<td>4.62±0.6</td>
<td>28.1±3.3</td>
</tr>
</tbody>
</table>

3.4 Measurement of recoil range distributions

In the experiment performed to study recoil range distributions, the activities induced in the individual catcher foils have been followed off-line one by one. The residues were identified by their characteristic $\gamma$ radiations and half lives. The experimental cross-sections corresponding to various radioactive residues in each catcher have been computed by using the intensities of identified $\gamma$ rays in individual catchers. The cross-section for a particular evaporation residue in each catcher was obtained using equation 3 of chapter II. In order to obtain the recoil range distributions, the measured cross-section for each evaporation residue in individual catcher was divided by the respective thickness of that catcher. The results of recoil range distribution (RRD) measurements for $^{16}O+^{169}Tm$ system at 86.6 MeV, are
tabulated in Tables 3.3.6 and 3.3.7, respectively.

**Table 3.3.6 Measured RRD for Ir, Os and Re isotopes**

<table>
<thead>
<tr>
<th>Cumulative catcher thickness (µg/cm²)</th>
<th>σ(^{(182)Ir}) (mb/mg/cm²)</th>
<th>σ(^{(182)Os}) (mb/mg/cm²)</th>
<th>σ(^{(181)Os}) (mb/mg/cm²)</th>
<th>σ(^{(181)Re}) (mb/mg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.8</td>
<td>-</td>
<td>-</td>
<td>825.9</td>
<td>2713.1</td>
</tr>
<tr>
<td>36.4</td>
<td>80.1</td>
<td>598.3</td>
<td>499.5</td>
<td>2301.3</td>
</tr>
<tr>
<td>63.8</td>
<td>80.3</td>
<td>491.6</td>
<td>647.1</td>
<td>2802.7</td>
</tr>
<tr>
<td>91.7</td>
<td>150.2</td>
<td>503.1</td>
<td>574.1</td>
<td>3302.5</td>
</tr>
<tr>
<td>120.3</td>
<td>-</td>
<td>647.2</td>
<td>794.7</td>
<td>3820.4</td>
</tr>
<tr>
<td>149.8</td>
<td>-</td>
<td>779.8</td>
<td>1203.6</td>
<td>4929.2</td>
</tr>
<tr>
<td>180</td>
<td>-</td>
<td>895.0</td>
<td>1252.8</td>
<td>5636.1</td>
</tr>
<tr>
<td>210.6</td>
<td>-</td>
<td>1010.2</td>
<td>1302.0</td>
<td>6343.0</td>
</tr>
<tr>
<td>241.9</td>
<td>-</td>
<td>1111.1</td>
<td>1508.9</td>
<td>6921.1</td>
</tr>
<tr>
<td>273.9</td>
<td>590.4</td>
<td>1040.4</td>
<td>1457.8</td>
<td>5879.3</td>
</tr>
<tr>
<td>306.1</td>
<td>730.2</td>
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<td>1480.8</td>
<td>6532.2</td>
</tr>
<tr>
<td>339.3</td>
<td>-</td>
<td>1111.1</td>
<td>1508.9</td>
<td>6921.1</td>
</tr>
<tr>
<td>373.2</td>
<td>3060.2</td>
<td>914.7</td>
<td>1130.0</td>
<td>5577.0</td>
</tr>
<tr>
<td>410.3</td>
<td>2370.1</td>
<td>700.8</td>
<td>932.6</td>
<td>3859.1</td>
</tr>
<tr>
<td>450.2</td>
<td>1410.5</td>
<td>545.0</td>
<td>645.5</td>
<td>2601.2</td>
</tr>
<tr>
<td>494.4</td>
<td>570.3</td>
<td>351.2</td>
<td>444.3</td>
<td>1580.7</td>
</tr>
<tr>
<td>540.5</td>
<td>-</td>
<td>-</td>
<td>242.0</td>
<td>-</td>
</tr>
<tr>
<td>587.6</td>
<td>-</td>
<td>-</td>
<td>183.7</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 3.3.7 Measured RRD for Re, Hf and Lu isotopes

<table>
<thead>
<tr>
<th>Cumulative catcher thickness (μg/cm²)</th>
<th>σ(^{178}\text{Re}) (mb/mg/cm²)</th>
<th>σ(^{175}\text{Hf}) (mb/mg/cm²)</th>
<th>σ(^{172}\text{Lu}) (mb/mg/cm²)</th>
<th>σ(^{171}\text{Lu}) (mb/mg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.8</td>
<td>-</td>
<td>710.5</td>
<td>122.5</td>
<td>331.4</td>
</tr>
<tr>
<td>36.4</td>
<td>93.1</td>
<td>716.4</td>
<td>185.6</td>
<td>379.4</td>
</tr>
<tr>
<td>63.8</td>
<td>75.7</td>
<td>720.3</td>
<td>421.7</td>
<td>498.3</td>
</tr>
<tr>
<td>91.7</td>
<td>-</td>
<td>710.2</td>
<td>263.6</td>
<td>441.2</td>
</tr>
<tr>
<td>120.3</td>
<td>-</td>
<td>1750.5</td>
<td>332.9</td>
<td>600.5</td>
</tr>
<tr>
<td>149.8</td>
<td>200.2</td>
<td>2002.4</td>
<td>302.2</td>
<td>350.1</td>
</tr>
<tr>
<td>180</td>
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References


Chapter IV

Computer Codes

In the present work, theoretical calculations of the excitation functions have been done using three different computer codes viz., ALICE-91[1], CASCADE[2] and PACE2[3] based on statistical models. A brief description of these codes and their parameters is given here.

4.1 ALICE-91

The code ALICE-91 [1] is based on the Weisskopf-Ewing model [4] for compound nucleus reaction (equilibrium) while pre-equilibrium emission is simulated within the framework of Hybrid/geometry dependent hybrid model [5, 6]. In this code the possibility of incomplete fusion has not been taken into account but it can compute statistical fission cross-sections utilizing Bohr-Wheeler approach with angular momentum dependent ground state and saddle point energies. The particles which could be emitted are neutrons, protons, deuterons and/or $\alpha$ particles. The code may calculate the reaction cross-section for the residual nuclei upto 11 mass and 9 atomic number units from the compound nucleus. Myers-Swiatecki/Lysekil mass formula [7] 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 [8] subroutines, although there is an option of classical sharp cut off model also. The transmission coefficients are calculated using
the parabolic model of Thomas [9] for heavy ions. Calculations in this code are done assuming equipartition of energy among the initially excited particles and holes. The important input parameters required in this code are, the level density parameter $a$, the initial exciton number $n_o$ and the mean free path (MFP) multiplier 'COST' along with the description of the projectile and target nucleus. The MFP for intranuclear transition rates may be calculated from the optical model of Becchetti and Greenlees [10] or from Pauli corrected nucleon-nucleon cross-sections [11, 12]. The MFP multiplier COST is used to adjust the nuclear mean free path in order to reproduce the experimental data. It accounts for the difference, if any, between the calculated and the actual MFPs for two-body residual interactions.

Level densities of the residue may be calculated either from the Fermi Gas model or from the constant temperature form. The Fermi gas model gives [13],

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

(1)

where, $\delta$ is the pairing term and $U$ is the excitation energy of the nucleus. The level density parameter $a$ is taken as $A/K$, where $A$ being the mass number of the nucleus and $K$ is an adjustable parameter. The level density $\rho(U)$ is given as [14],

$$
\rho(U) \propto \frac{1}{T} e^{U/T}
$$

(2)

The differential cross-section for emitting a particle with channel energy $\varepsilon$ may be written as (cross-section per unit energy to emit a particle of type
where, $A$ is the de-Broglie wavelength of the incident ion, $T_I$ the transmission coefficient of the $I^{th}$ partial wave of the incident ion, $\rho(\varepsilon, J)$ the spin dependent level density for the residual nucleus, $D$ the integral of numerator over all particles and emission energies, $\varepsilon$ the excitation energy of the compound nucleus. $S_{\nu}$ is the intrinsic spin of the particle $\nu$, $T^I_{\nu}(\varepsilon)$ is the transmission coefficient for the particle $\nu$ with kinetic energy $\varepsilon$ and orbital angular momentum $l$.

In the Weisskopf-Ewing calculations, the nuclear moment of inertia is infinite and hence there is no energy tied to rotation, thus no level density cut off at high spin. This code does not take into account the angular momentum involved in heavy ion reactions. 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 $J$, can not have energy below a minimum value $E_J^{\text{min}}$,

$$E_J^{\text{min}} \approx J(J + 1)\frac{\hbar^2}{2I}$$  \hspace{1cm} (4)

here, $I$ being the moment of inertia of the composite nucleus.

If in the last stages of nuclear de-excitation, higher angular momentum of the nucleus inhibits particle emission more than it does $\gamma$ emission, then, the peak of the excitation functions corresponding to particle emission mode

\hspace{1cm} \text{\ldots}
will be shifted to higher energy [15]. A similar shift may also be produced if the mean energy of the evaporated particles increases with increasing nuclear spin. One way of obtaining an estimate of the overall energy shift is from the nuclear rotational energy. For a rigid body moment of inertia, \( E_{\text{rot}} \approx (m/M)E_{\text{lab}} \), where, \( m/M \) is the ratio of the projectile and target masses and \( E_{\text{lab}} \) is the incident energy [15]. To account for the large angular momentum imparted to the composite system, it is desirable to shift the calculated excitation functions by the amount approximately equal to \( E_{\text{rot}} \).

4.2 CASCADE

The code CASCADE [2] is based on Hauser-Feshbach theory[16] of compound nucleus and is frequently used to calculate the reaction cross-sections for heavy ions. It is assumed that the compound nucleus has lost all its memory about the formation by the time a thermodynamic equilibrium is attained. This code computes the reaction cross-sections for long lived or stable product nuclei in the ground state formed by the de-excitation of the compound nucleus. The decay probabilities are determined by the level densities of the daughter nuclei and the barrier penetrabilities for the various channels. This code does not take into account the possibility of pre-equilibrium emission and/or incomplete fusion. However, the present version of the code includes fission competition. The liquid drop fission barrier is assumed. Some of the input parameters like the mass of nuclide and the transmission coefficients for the emitted particles are computed using codes MASS and TLCALC, respectively, for the region of interest and stored permanently on the disc. The optical model potentials of Becchetti and Greenlees [10] are
used for calculating the transmission coefficients for protons and neutrons, and optical model potential of Satchler [17] is used for $\alpha$ particles. Fermi gas model is used for calculating the level densities for the product nuclei.

At low excitation energies, the parameters can be determined empirically. However, attention is required for the spin dependence of level densities in the region of high excitation. This is because of the high angular momenta involved in heavy ion reactions.

The partial cross-section for the formation of the compound nucleus of spin $J$ and parity $\pi$ from a projectile and a target nuclei of spins $J_P$ and $J_T$ respectively, at center of mass energy $E$ is given by [18],

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

(5)

here, $T_L$ the transmission coefficients, depend on the energy and the orbital angular momentum. $S=(J_P + J_T)$ is the channel spin. The $T_L$ as a function of angular momentum is approximated by a Fermi distribution,

$$T_L = \frac{1}{1 + \exp[-(L - L_0)/d]}$$

(6)

Where, $L_0$ is the grazing angular momentum and $d$ is the diffuseness parameter.

In case of even-even nuclei, the spin of the projectile and the target is taken as zero. The partial cross-section is given as,
Thus the total cross-section is given by,

\[ \sigma_t = \frac{\pi \lambda^2}{4\pi^2} \sum_{L=0}^{\infty} (2L + 1) T_L(E) \]  

The total fusion cross-section for the maximum angular momentum \( L_c \) of the CN is given by;

\[ \sigma_f = \frac{\pi \lambda^2}{4\pi^2} \sum_{L=0}^{L_c} (2L + 1) T_L(E) \]  

In statistical model calculations, the critical angular momentum \( L_c \) for CN fusion may be sharp limit, or may have some overlap from \( L_c \) to higher \( L \) determined by the diffuseness parameter \( d \).

The level density \( \rho \) at an excitation energy \( E \) and spin \( J \) is given by [19],

\[ \rho(E, J) = \omega(E, M = J) - \omega(E, M = J + 1) \]  

with the level densities

\[ \omega(E, M) = \omega(E - M^2/aR, 0), \omega(E, 0) = \frac{1}{12\sqrt{Ra^2t^3}} \exp(2\sqrt{aU}) \]  

and the equation of state,

\[ U = E - \Delta = at^2 - \frac{3}{2}t \]
Here, $a$ is the level density parameter, which determines the energy dependence, $\Delta$ is the pairing energy which determines the zero point of the effective excitation energy $U = E - \Delta$ and $t$ is the thermodynamic temperature given by the equation of state. The spin dependence is determined by the parameter $aR = 2I/\hbar^2$ where, $I$ is the effective moment of inertia obtained from the low lying states of the isotope.

$$I = \frac{2}{5}mr^2$$

(13)

with, $r = r_o A^{1/3}$

The level density formula implies a yrast line,

$$E_{rot}(J) = J(J + 1)/aR + \Delta = \frac{J(J + 1)\hbar^2}{2I} + \Delta$$

(14)

when large range of excitation energies are involved the parameters used should be energy dependent. therefore, the entire energy region is divided into three regions.

**Region I (Low excitation energy $E \leq 3$ to 4 MeV)**

Here, the experimentally known levels are used.

**Region II (Medium excitation energy 4 $\leq E \leq 10$ MeV)**

Here, the analytic level density formula is applied. The parameters $a$ and $\Delta$ can be determined empirically for each nucleus as was done by Vonach et. al., [20] and Dilg et. al., [21].
Region III (High excitation energy $E \geq E_{LDM}$)

In this region, very little is known about the level densities. So it is assumed that at a sufficiently high excitation energy $E_{LDM}$, all nuclei behave as predicted by liquid drop model (LDM). Analytical form of Fermi gas level density is used here and both parities are assumed equiprobable. The parameter $a=a_{LDM}$ is taken to be $(1/8) A \text{MeV}^{-1}$. The pairing shift $\Delta_{LDM}$ is calculated assuming that the virtual ground state for the level density in this region should coincide with the ground state energy of a spherical liquid drop which can be calculated from one of the following options (1) Myers-Swiatecki mass formula (2) Dilg et. al.[21] (3) Kataria[22]. The moment of inertia which determines the spin dependence is taken to be that of a deformable liquid drop with gyrostatic motion.

4.3 PACE2

The code PACE2[3] is used to calculate the reaction cross-section of highly excited compound nucleus having higher angular momentum. In this code the most of required input parameters have been used as default except the charge and mass of the projectile and target nucleus. Fission is considered as a decay mode, while the incomplete fusion is not taken into account. Since angular momentum conservation is explicitly taken into account at each step, the calculated excitation functions need not be shifted for rotational energy correction.

The partial cross-section for compound nucleus formation at angular momentum $L$ and specific bombarding energy is given by,
where, $\lambda$ is the reduced wavelength and $T_L$ is given by,

$$T_L = \left[1 + \exp(L - L_{max})/\delta\right]^{-1}$$

where, $\delta$ is the diffuseness parameter and $L_{max}$ is determined by the total fusion cross-section,

$$\sigma_F = \sum_{L=0}^{\infty} \sigma_L$$

The transmission coefficients for the evaporation of light particles (n, p, $\alpha$), during the first step of de-excitation are obtained by optical model calculations. In this code the fission decay mode may be considered using a rotating liquid fission barrier routine[3]. Angular momentum projections are calculated at each stage of de-excitation which enables the determination of the angular distribution of the emitted particles. It may be pointed out that PACE2 code carries out only the statistical equilibrium model calculations and does not take PE emission into consideration.
References


77


Chapter V
Results and Discussion

Excitation functions (EFs) for twenty three reactions induced by $^{12}\text{C}$ in $^{128}\text{Te}$ and by $^{16}\text{O}$ in $^{159}\text{Tb}$ and $^{169}\text{Tm}$ target nuclides have been measured at energies below 7 MeV/nucleon. A list of these reactions is given below:

$^{128}\text{Te}(^{12}\text{C},3n)^{137}\text{mCe}$, $^{128}\text{Te}(^{12}\text{C},5n)^{135}\text{Ce}$, $^{128}\text{Te}(^{12}\text{C},4pn)^{135}\text{La}$, $^{128}\text{Te}(^{12}\text{C},\alpha 3n)^{133}\text{mBa}$, $^{128}\text{Te}(^{12}\text{C},\alpha 5n)^{131}\text{Ba}$, $^{128}\text{Te}(^{12}\text{C},\alpha 4pn)^{131}\text{mTe}$, $^{159}\text{ Tb}(^{16}\text{O},3n)^{172}\text{Ta}$, $^{159}\text{ Tb}(^{16}\text{O},4n)^{171}\text{Ta}$, $^{159}\text{ Tb}(^{16}\text{O},5n)^{170}\text{Ta}$, $^{159}\text{ Tb}(^{16}\text{O},p3n)^{171}\text{Lu}$, $^{159}\text{ Tb}(^{16}\text{O},p4n)^{170}\text{Lu}$, $^{159}\text{ Tb}(^{16}\text{O},\alpha)^{171}\text{Hf}$, $^{159}\text{ Tb}(^{17}\text{O},3n)^{170}\text{ Hf}$, $^{159}\text{ Tb}(^{17}\text{O},\alpha 2n)^{169}\text{Hf}$, $^{159}\text{ Tb}(^{17}\text{O},2\alpha 2n)^{165}\text{Tm}$, $^{159}\text{Tm}(^{16}\text{O},3n)^{182}\text{Ir}$, $^{159}\text{Tm}(^{16}\text{O},4n)^{181}\text{Ir}$, $^{159}\text{Tm}(^{16}\text{O},p2n)^{182}\text{Os}$, $^{159}\text{Tm}(^{16}\text{O},p3n)^{181}\text{Os}$, $^{159}\text{Tm}(^{16}\text{O},\alpha)^{181}\text{Re}$, $^{159}\text{Tm}(^{16}\text{O},\alpha 3n)^{178}\text{Re}$, $^{159}\text{Tm}(^{16}\text{O},2\alpha pn)^{175}\text{Hf}$ and $^{169}\text{Tm}(^{16}\text{O},3\alpha n)^{172}\text{Lu}$.

The measured EFs for these reactions are presented in Figs.5.1.1 to 5.3.6. The analyses of excitation functions have been performed using three different computer codes viz., ALICE-91[1], CASCADE[2] and PACE2[3]. To the best of our knowledge measurement and analysis of these EFs are being reported for the first time. To separate out the relative contributions of complete and incomplete fusion, the recoil range distribution of various residues produced in the interaction of $^{16}\text{O}$ with $^{169}\text{Tm}$ have also been measured at 86.6 MeV. A detailed description of the measurements and computer codes used in the present analysis has already been given in Chapters III and IV, respectively. The vertical error bars presented in the experimental cross-sections represent
the overall errors in the measured values as discussed in Chapter II. The size of the data points include the uncertainty in the incident energies. Details of the calculations done using different codes, the parameters involved and the analysis of the EFs are presented in the following;

5.1 Analysis with Code ALICE-91

The code ALICE-91[1] has been developed by M. Blann, to account for the equilibrium (CN) as well as pre-equilibrium (PE) emission in light and heavy ion induced reactions. The CN calculations in this code are performed using Weisskopf-Ewing model[4], however, PE component is simulated using Hybrid/Geometry Dependent Hybrid model[5]. In this code the level density parameter $\alpha$, the mean free path multiplier $COST$ and initial exciton number $n_0$ are some of the important parameters. The level density parameter $\alpha$ affects the equilibrium as well as pre-equilibrium component, while the initial exciton number $n_0$ and mean free path multiplier $COST$ govern the pre-equilibrium component. The level density parameter $\alpha$ is calculated from the expression $\alpha = A/K$, where, $A$ is the mass number of the residual nucleus and $K$ is a parameter which can be varied to match the experimental data. Calculations have been performed for different values of these parameters. As an example the effect of variation of parameter $K$ on calculated EFs using code ALICE-91 for the reactions $^{128}Te(^{12}C, 3n)^{137m}Ce$, $^{128}Te(^{12}C, 5n)^{133}Ce$, $^{128}Te(^{12}C, p4n)^{135}La$, $^{128}Te(^{12}C, \alpha3n)^{133m}Ba$ and $^{128}Te(^{12}C, \alpha5n)^{131}Ba$ is shown in Figs 5.1.1 (a-e). As can be seen from these figures, the calculated EFs satisfactorily reproduce the experimental data for $^{12}C + ^{128}Te$ and $^{16}O + ^{159}Tb$ systems with $K = 18$. However, a value of $K = 22$ satisfactorily
Figs. 5.1.1 Experimentally measured and theoretically calculated EFs using code ALICE-91. Effect of variation of parameter K on calculated EFs is also shown.
reproduce the experimental data for $^{16}O + ^{169}Tm$ system. These values of $K$ are consistent with the values given by Dilg et. al.,[6]. In code ALICE-91 which uses the hybrid model, the intermediate states of the system are characterised by the excitation energy $E$ and number $n_p$ of excited particle 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. It is of particular interest to look for the initial exciton number required to reproduce the data. Calculations have been done using different values of initial exciton number $n_0$. For $^{12}C$ induced reactions a value of $n_0=12$ with configuration $(6p + 6n + 0h)$ and for $^{16}O$ induced reactions a value of $n_0=16$ $(8p + 8n + 0h)$ has been found to satisfactorily reproduce the experimental data, where, $p$, $n$ and $h$ represent the number of excited protons, neutrons and holes respectively. As a representative case, in order to see the effect of variation in the values of the initial exciton number $n_0$, on calculated EFs, calculations for two different initial exciton configurations i.e., $n_0=12$ $(6p + 6n + 0h)$ and $n_0 = 14(6p + 7n + 1h)$ for reaction $^{128}Te(^{12}C,3n)^{137m}Ce$ is shown in Figs.5.1.2 along with the CN calculations. It may be seen from these figures that lower value of initial exciton number gives, in general, larger pre-compound contributions. It is because of the fact that lower value of the $n_0$ means larger number of two-body interactions prior to the establishment of equilibrium characteristic of CN resulting in larger pre-compound contribution. In all these calculations the value of parameter $COST$ has been taken consistently equal to 2. Further, it has been observed that the calculated EFs are not very much affected.
Fig. 5.1.2 Experimentally measured and theoretically calculated excitation functions using code ALICE-91 for CN and pre-compound reactions. Effect of variation of parameter $n_0$ is also shown.
by the variation in the value of parameter $COST$, in this energy range. As a representative case the effect of variation of parameter $COST$ on the calculated EF for the reaction $^{128}Te(^{12}C, 3n)^{137m}Ce$ is shown in Fig.5.1.3.

It may be pointed out that the maxima of the measured EFs peak at energies higher than the corresponding calculated EFs. This is expected, since in ALICE-91 calculations the angular momentum effects have not been taken into account. In HI induced reactions incident particle imparts relatively larger angular momentum to the composite system. If, in the last stages of nuclear de-excitation, higher angular momentum inhibits particle emission more than it does $\gamma$ emission, then, the peak of excitation function corresponding to the particle emission mode will be shifted to higher energies [7]. The effect is more pronounced in heavy ion (HI) reactions as compared to the light ion reactions, since the rotational energy is much greater in case of HI reactions. An estimate of the possible shift due to angular momentum effects may be calculated from the nuclear rotational energy. For a rigid body, the rotational energy $E_{rot} \approx (m/M)E_{lab}$, where $m/M$ is the ratio of the projectile and the target nucleus masses and $E_{lab}$ is the incident energy[7]. Since the angular momentum effects have not been considered in the Weisskopf-Ewing calculations of present version of ALICE-91 code, it is desirable to shift the calculated excitation functions by the amount approximately equal to $E_{rot}$ as calculated above. It has been observed that the ALICE-91 calculations satisfactorily reproduce the experimental data when the energy scale of the calculated excitation functions are shifted by respective $E_{rot}$ values. As an example, the calculated EFs with an energy shift equal to $E_{rot}$ for reactions in
Fig. 5.1.3 Experimentally measured and theoretically calculated EFs using code ALICE-91. Effect of variation of parameter COST on calculated EFs is also shown.
$^{159}Tb(16O,xn)^{175-2}Ta$ (x=3-5) and $^{159}Tb(16O,p3n)^{173}Hf$ are shown in Figs 5.1.4 (a-d), while for reactions $^{169}Tm(16O,3n)^{182}Ir$, $^{169}Tm(16O,4n)^{181}Ir$, $^{169}Tm(16O,p2n)^{182}Os$, and $^{169}Tm(16O,p3n)^{181}Os$ are shown in Figs 5.1.5 (a-d), respectively. The unshifted calculated EFs are also shown by dotted lines in these figures for comparison. It may, however, be pointed out that the experimentally measured values of cross-section for the reactions $^{159}Tb(16O,4n)^{171}Ta$, $^{159}Tb(16O,p3n)^{171}Hf$ (Figs. 5.1.4 b and c) and $^{169}Tm(16O,4n)^{181}Ir$ (Figs. 5.1.5 b) are relative, since the absolute intensities of the $\gamma$ rays are not known, only relative intensities are available[8], hence the measured value of the EFs are not in agreement with the theoretically calculated EFs using code ALICE-91. The enhancement in the measured EFs for the reactions $^{128}Te(^{12}C,\alpha3n)^{133m}Ba$ and $^{128}Te(^{12}C,\alpha5n)^{131}Ba$, in general, as compared to the theoretical predictions as shown in Figs 5.1.1 (d and e), may be attributed to the fact that these channels may be populated not only by the CF of $^{12}C$ but may also have significant contribution of ICF of $^{12}C$ (if $^{12}C$ breaks up into $^8Be$ and $\alpha$ particles) with $^{128}Te$. It may be observed from the Figs 5.1.1 that the measured cross-sections for all cases in the vicinity of the Coulomb barrier is considerably higher than the calculated using code ALICE-91. Though, no definite reason may be assigned for this but it may be attributed to the distortion in the shape of effective potential between the interacting ions at small separations. The observed enhancement of measured EFs over their calculated values for the reactions $^{159}Tb(16O,\alpha)^{171}Hf$, $^{159}Tb(16O,\alpha n)^{170}Hf$, $^{159}Tb(16O,\alpha2n)^{169}Hf$ [Figs. 5.1.6 (b-d)], and for reactions $^{169}Tm(16O,\alpha)^{181}Re$, $^{169}Tm(16O,\alpha3n)^{178}Re$ [Figs. 5.1.8 (b and c)], may be attributed to the fact that these channels are populated not only by the CF.
Figs. 5.1.4 Experimentally measured and theoretically calculated EFs using code ALICE-91. Effect of $E_{rot}$ on calculated EFs is also shown.
Fig. 5.1.5 Experimentally measured and theoretically calculated EFs using code ALICE-91. Effect of $E_{\text{rot}}$ on calculated EFs is also shown.
Figs. 5.1.6 Experimentally measured and theoretically calculated EFs using code ALICE-91.
of $^{16}\text{O}$ but also may have significant contributions from ICF (if $^{16}\text{O}$ breaks up into $\alpha$, $^8\text{Be}$ and $^{12}\text{C}$ fragments). It may be pointed out that ALICE-91 does not take into account the incomplete fusion in calculations. Further, the theoretical calculations for reactions $^{128}\text{Te}(^{12}\text{C},\alpha^4p\pi)n^{131m}\text{Te}$, (Fig 5.1.1 f) $^{159}\text{Tb}(^{16}\text{O},2\alpha^2n)^{165}\text{Tm}$ (Fig 5.1.7), $^{169}\text{Tm}(^{16}\text{O},3\alpha\pi)n^{172}\text{Lu}$ and $^{169}\text{Tm}(^{16}\text{O},3\alpha^2n)^{171}\text{Lu}$ (Figs 5.1.8 c and d) are not shown since the calculated values of cross-sections for these cases are negligibly small (less than 0.01 mb). As such, it may be concluded that the major contribution to these reaction channels come from the incomplete fusion.

5.2 Analysis with Code CASCADE

The code CASCADE[2] is based on Hauser-Feshbach theory[9] and does not consider the possibility of incomplete fusion (ICF) and/or PE emission. 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 $F_\alpha$, are the two important parameters which may be varied to match the experimental data. Fermi-gas model is used in this code to calculate the level densities of the product nuclei. The transmission coefficients, in these calculations are generated using the optical model potentials of Becchetti and Greenlees[10] for neutrons and protons and that of Satchler[11] for $\alpha$-particles. The effect of variation in the values of level density parameter constant $K$ on the calculated EFs for several reactions are shown in Figs 5.2.1 (a-e), 5.2.3 and 5.2.4 (a-d). The measured cross-sections for the corresponding reactions are shown in these figures. It may however, be noted that theoretical calculations with $K = 8$ for the reactions $^{159}\text{Tb}(^{16}\text{O},\alpha)^{171}\text{Lu}$ and
Fig. 5.1.7 Experimentally measured excitation functions.
Figs. 5.1.8 Experimentally measured and theoretically calculated EFs using code ALICE-91.
Figs. 5.2.1 Experimentally measured and theoretically calculated EFs using code CASCADE. Effect of variation of parameter K on calculated EFs is also shown.
Figs. 5.2.2 Experimentally measured and theoretically calculated EFs using code CASCADE. Effect of variation of parameter K is also shown.
Figs. 5.2.3 Experimentally measured and theoretically calculated EFs using code CASCADE.
Figs. 5.2.4 Experimentally measured and theoretically calculated EFs using code CASCADE. Effect of variation of parameter K is also shown.
Figs. 5.2.5 Experimentally measured and theoretically calculated EFs using code CASCADE.
$^{159}Tb(^{16}O,\alpha n)^{170}Lu$ gives negligible cross-sections and therefore, not shown in Figs. 5.2.3 b and c. As can be observed from these figures, a value of $K = 14$ is found to reproduce the data satisfactorily, in general.

The parameter $F_\theta$, which is the ratio of actual moment of the inertia of the excited system to rigid body moment of inertia is also a free parameter of the code. The value of $F_\theta$ has been varied from 0.55 to its default value 0.85. As a representative case the effect of variation in parameter $F_\theta$ on calculated EFs for reactions $^{128}Te(^{12}C,3n)^{137m}Ce$, $^{128}Te(^{12}C,5n)^{135}Ce$, $^{128}Te(^{12}C,p4n)^{135}La$ and $^{128}Te(^{12}C,\alpha 3n)^{133m}Ba$ are shown in Figs. 5.2.6 (a-d), and found to have negligible effect on calculated EFs.

In HI induced reactions of interest the high angular momentum and excitation energy is expected to have considerable influence on the de-excitation cascade. Since in HI reactions increasing excitation energy also increases the angular momentum, the deformation of the nucleus due to 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 into the deviation of yrast line from that calculated assuming the nucleus to be a rigid sphere. The level density parameter $a_f$ at the saddle point which is obtained from the relation $a_f = A/D_{AF}$, where, $A$ is the mass number of the compound nucleus and $D_{AF}$ is a parameter whose default value is 8 is also found to influence the calculated EFs considerably. As such the influence of variation of $D_{AF}$ from 8 to 11 on calculated EFs for reactions in $^{12}C + ^{128}Te$ system has also been studied. The resulting excitation functions using these values of parameters $D_{AF}(= 8 - 11)$, $K=14$ and $F_\theta=0.85$ are
Figs. 5, 2, 6. Experimentally measured and theoretically calculated EFs using code CASCADE. Effect of variation of parameter $F_0$ on calculated EFs is also shown.
shown in Figs 5.2.7 (a-e). As can be seen from these figures, the parameter \( D_{AF} \) has a considerable influence on calculated EFs in higher energy region. Further, a value of \( D_{AF} = 11 \) and \( F_0 = 0.85 \), gives a satisfactorily agreement with experimental data even in high energy region. As can be seen from these figures that the EFs for all reactions are qualitatively in good agreement with theoretical calculations done using code CASCADE in the peak region. The higher values of experimental cross-sections in the tail portion of EF for the reaction \(^{128}Te(\alpha, 3n)^{137m}Ce\) (Fig. 5.2.7 a) as compared to the theoretical calculations may be attributed to the PE-emission which is dominant mode of reaction at higher energies and has not been considered in the CASCADE calculations. For reactions \(^{159}Tb(\alpha, 4n)^{171}Ta\), \(^{159}Tb(\alpha, 3n)^{171}Hf\) (Figs.5.2.2 b and d) and \(^{169}Tm(\alpha, 4n)^{181}Ir\) (Figs.5.2.4 b), as can be seen from these figures, the calculated EFs in general do not match the measured EFs, they reproduce only the trend of EFs[8]. It may be mainly due to the fact that the measured cross-sections are relative as only the relative intensities of \( \gamma \)-rays from the residues produced in these reactions are available. The cases of reactions \(^{159}Tb(\alpha, \alpha)^{171}Hf\), \(^{159}Tb(\alpha, \alpha n)^{170}Hf\), \(^{159}Tb(\alpha, \alpha 2n)^{169}Hf\), \(^{169}Tm(\alpha, \alpha)^{181}Re\) and \(^{169}Tm(\alpha, \alpha 3n)^{178}Re\) need special mention. In these cases, the theoretically calculated EFs do not match with the experimentally measured values [Figs 5.2.3 (b-d) and Figs 5.2.5 (a and d)]. The theoretically calculations are lower by several orders of magnitude as compared to the experimentally measured EFs. This may be attributed to the fact that these channels may be populated not only by the CF of \(^{16}O\) but also may have significant contributions from ICF (if \(^{16}O\) breaks up into \( \alpha, \alpha 8\)Be and \( \alpha 12\)C fragments). Further, for the reactions
Figs. 5.2.7 Experimentally measured and theoretically calculated EFs using code CASCADE. Effect of variation of parameter $D_{AF}$ on calculated EFs is also shown.
the calculated values of EFs using code CASCADE are negligibly small (less than 0.01 mb) and could not be shown in the figures. Since, the ICF has not been considered in CASCADE calculations, it may be concluded that the major contribution to these reaction channels comes from the incomplete fusion.

5.3 Analysis with Code PACE2

The code PACE2[3] is based on statistical approach. In this code the deexcitation of the CN is followed by Monte Carlo procedure. The angular momentum projections are calculated at each stage of deexcitation which enables the determination of the angular distribution of the emitted particles. In this code the level density parameter is one of the important parameters which may be varied to match the experimental data. The effect of variation in level density parameter constant $K=\{8.0$ and $10\}$ on calculated EFs for the reactions $^{128}Te(^{12}C,3n)^{137}mCe$, $^{128}Te(^{12}C,5n)^{135}Ce$, $^{128}Te(^{12}C,p4n)^{135}La$, $^{128}Te(^{12}C,\alpha3n)^{133}mBa$ is shown in Figs 5.3.1 (a-d), while for the reactions $^{159}Tb(^{16}O,3n)^{172}Ta$, $^{159}Tb(^{16}O,4n)^{171}Ta$, $^{159}Tb(^{16}O,5n)^{170}Ta$, $^{159}Tb(^{16}O,p3n)^{171}Lu$, $^{159}Tb(^{16}O,p4n)^{170}Lu$, $^{159}Tb(^{16}O,\alpha)^{171}Hf$, $^{159}Tb(^{16}O,\alpha n)^{170}Hf$, $^{159}Tb(^{16}O,\alpha2n)^{169}Hf$ and $^{159}Tb(^{16}O,2\alpha2n)^{165}Tm$ is shown in Figs 5.3.2 (a-d)-5.3.4, respectively.

As can be observed from these figures that a value of $K=8.0$ satisfactorily reproduce the measured EFs in general for all reactions in $^{12}C+^{128}Te$ and $^{16}O+^{159}Tb$ systems.
Figs. 5.3.1 Experimentally measured and theoretically calculated EFs using code PACE2. Effect of variation of parameter K on calculated EFs is also shown.
Figs. 5.3.2 Experimentally measured and theoretically calculated EFs using code PACE2. Effect of variation of parameter K on calculated EFs is also shown.
Figs. 5.3.3 Experimentally measured and theoretically calculated EFs using code PACE2. Effect of variation of parameter K on calculated EFs is also shown.
Fig. 5.3.4 Experimentally measured and theoretically calculated EFs using code PACE2.
However, a value of $K = 16$ is found to satisfactorily reproduce the measured EFs for $^{16}O + ^{169}Tm$ system. The effect of variation of $K$ for the reactions $^{169}Tm(^{16}O, 3n)^{182}Ir$, $^{169}Tm(^{16}O, 4n)^{181}Ir$, $^{169}Tm(O, p2n)^{182}Os$ and $^{169}Tm(^{16}O, p3n)^{181}Os$ are shown in Figs 5.3.5 (a-d). Once again, as may be observed in Figs. 5.3.6 (a and b) the measured EFs are higher than the theoretical predictions. In case of reactions $^{169}Tm(^{16}O, 2\alpha p)n^{175}Hf$ and $^{169}Tm(^{16}O, 3\alpha)n^{172}Lu$, the theoretical predictions are negligible and hence not shown in figures, while the measured cross-sections are comparatively larger. This enhancement of the measured cross-sections by several orders of magnitude than their theoretical predictions may be associated with the ICF process.

### 5.4 Recoil range distributions

In the previous section, enhancement of EFs by several orders of magnitude have been observed as compared to theoretical calculations in the reactions $^{169}Tm(^{16}O, \alpha)^{181}Re$, $^{169}Tm(^{16}O, \alpha3n)^{178}Re$, $^{169}Tm(^{16}O, 2\alpha pn)^{175}Hf$, $^{169}Tm(^{16}O, 3\alpha n)^{172}Lu$ and $^{169}Tm(^{16}O, 3\alpha 2n)^{171}Lu$, which may have substantial contributions of incomplete fusion.

In order to separate out the relative contribution of complete and incomplete fusion, the recoil range distributions (RRDs) of the residues produced in the interaction of $^{16}O$ with $^{169}Tm$ have been measured at 86.6 MeV. Differential recoil range distributions (as detailed in Chapter II) for various evaporation residues are shown in Figs.5.4.1 (a-h). Solid lines guide the eye to the experimental data. As can be seen from these figures, the recoil range...
Figs. 5.3.5 Experimentally measured and theoretically calculated EFs using code PACE2. Effect of variation of K is also shown.
Figs. 5.3.6 Experimentally measured and theoretically calculated EFs using code PACE2.
Fig. 5.4.1 Experimentally measured recoil range distributions for the residues produced in $^{16}$O+$^{169}$Tm at 86.6 MeV.
distributions for $^{182}Ir$ and $^{181,182}Os$ isotopes produced via i.e., $(^{16}O,3n)$, $(^{16}O,p3n)$ and $(^{16}O,p2n)$ channels respectively, have a peak at only one value of cumulative catcher thickness ($\approx 350 \mu g/cm^2$). The RRD of $Ir$ and $Os$ isotopes are nearly Gaussian having peaks at a depth nearly corresponding to the expected recoil range of the $^{185}Ir$ nucleus in Aluminium, calculated using the classical approach and the stopping power tables of Northcliffe and Schilling[15], meaning thereby that these products are formed by complete fusion process only, followed by the evaporation of n and/or p. However, for $^{169}Tm(^{16}O,2p2n)^{181}Re$ reaction, the RRD has two peaks one at a relatively lower value of cumulative catcher thickness ($\approx 250 \mu g/cm^2$ and the other at ($\approx 350 \mu g/cm^2$) respectively. In Fig.5.4.1(d), the maxima at larger value of cumulative thickness ($\approx 350 \mu g/cm^2$) corresponds to the fraction of the residue produced through complete fusion, while the peak at relatively shorter range of cumulative catcher thickness ($\approx 250 \mu g/cm^2$) may be attributed to the fact that the residue $^{181}Re$ is produced via incomplete fusion also. It may be pointed out that the expected data points for the peak positions of RRD (at $\approx 250 \mu g/cm^2$ and $\approx 350 \mu g/cm^2$) for the residue $^{178}Re$ [Fig.5.4.1(e)] produced via $(^{16}O,3\alpha n)$ reaction could not be obtained due to the short half-life (13.3 m) of the residue.

As expected, the observed recoil range distributions for the $^{175}Hf$ isotopes produced via $^{169}Tm(^{16}O,2\alpha pn)$ reaction [Fig. 5.4.1 (f)], have three peaks at cumulative thicknesses $\approx 370 \mu g/cm^2$, $\approx 260 \mu g/cm^2$ and $\approx 150 \mu g/cm^2$ corresponding to the residue $^{175}Hf$ produced via three different channels i.e.,

1. Complete Fusion of $^{16}O$ with $^{169}Tm$, forming the composite nucleus
followed by the emission of a proton, a neutron and two $\alpha$-particles.

2. Incomplete Fusion of $^{16}O$, if it is assumed that $^{16}O$ breaks up into $^{12}C$ and an $\alpha$-particle and fragment $^{12}C$ fuses with $^{169}Tm$, forming the composite nucleus $^{181}Re$, followed by the emission of a proton, a neutron and two $\alpha$-particles.

3. Incomplete Fusion of $^{16}O$, assuming that $^{16}O$ breaks up into two $^{8}Be$ fragments and one of these fragments fuses with $^{169}Tm$, forming the composite nucleus $^{177}Ta$, followed by the emission of a proton, a neutron.

For the reactions $^{169}Tm(^{16}O, 3\alpha n)^{172}Lu$ and $^{169}Tm(^{16}O, 3\alpha 2n)^{171}Lu$, the measured RRDs show two peaks at relatively lower value of cumulative catcher thicknesses, $\approx 75 \mu g/cm^2$ and $\approx 150 \mu g/cm^2$. This indicates that these products are not only populated by the complete fusion process but by some other process in which the linear momentum transfer is less than that for complete fusion process. This is possible when only a part of projectile fuses with the target (incomplete fusion) and rest of it goes with a velocity nearly equal to the velocity of the projectile. As such in these reactions the contribution of complete fusion is negligible.

In order to separate out the quantitative relative contributions of complete and incomplete fusion in $^{169}Tm(^{16}O, 2p2n)^{181}Re$ reaction, the experimentally measured RRDs has been fitted with Gaussian peaks as shown in Fig 5.4.2 and the area under the two peaks has been computed. The relative contributions of the two processes are obtained by dividing the area of the corresponding peak by the total area. The incomplete fusion contribution in
Fig. 5.4.2 Gaussian fit to the recoil range distribution
this case is found to be 65% with an uncertainty of 5%.

Similarly, for the reaction \(^{169}Tm(^{16}O, 2\alpha p)^{175}Hf\), the experimentally measured RRDs has been fitted with three Gaussian peaks at cumulative thicknesses \(\approx 150\mu g/cm^2\), \(\approx 250\mu g/cm^2\) and \(\approx 370\mu g/cm^2\) as shown in Fig 5.4.3. The area under each peak has been computed and divided by the total area to get the relative contributions for the process of interest. The relative contributions of CF, ICF for the fusion of fragment \(^{12}C\) and ICF contribution corresponding to the fusion of \(^8Be\) are found to be \(\approx 25\%\), \(\approx 29\%\) and \(\approx 46\%\), respectively, for this channel.

In case of reactions \(^{169}Tm(^{16}O, 3\alpha n)^{172}Lu\) and \(^{169}Tm(^{16}O, 3\alpha 2n)^{171}Lu\), shown in Figs. 5.4.1 (g and h), the RRD have only two peaks at relatively lower values of ranges which may be attributed to ICF processes. The relative contributions of ICF (as indicated in Figs. 5.4.4 and 5.4.5) of \(\alpha\)-particle and \(^8Be\) have been found to be \(\approx 20\%\) and \(\approx 80\%\) for the residue \(^{172}Lu\) while \(\approx 74\%\) and \(\approx 26\%\), respectively for residue \(^{171}Lu\).

In light of the above it may be concluded that the ICF plays an important role in the heavy-ion reactions. More detailed studies, may, however, be done by measuring the angular distribution of projectile fragments.
Fig 5.4.3 Gaussian fit to the recoil range distribution

$^{169}\text{Tm}(^{16}\text{O},2\alpha \text{pn})^{175}\text{Hf}$

Yield (mb/mg cm$^{-2}$)

Cumulative thickness ($\mu$g/cm$^2$)

- EXPERIMENTAL
- GAUSSIAN FIT FOR ICF OF $^8\text{Be}$
- GAUSSIAN FIT FOR ICF OF $^{12}\text{C}$
- GAUSSIAN FIT FOR CF
Fig 5.4.4 Gaussian fit to the recoil range distribution
Fig 5.4.5 Gaussian fit to the recoil range distribution
References


List of publications

1. Measurement of Recoil Range Distribution in $^{12}\text{C} + ^{165}\text{Ho}$ below 7 Mev/nucleon:

2. Decay of $^{177}\text{Ta}$ compound nucleus: Comparison of the excitation functions for the reaction residues occurring in $^{12}\text{C} + ^{165}\text{Ho}$ and $^{14}\text{N} + ^{163}\text{Dy}$ reactions:

3. Complete and Incomplete Fusion: Measurement and Analysis of Excitation Function in $^{12}\text{C} + ^{128}\text{Te}$ system at energies near and above the Coulomb barrier:

4. Measurement and analysis of cross-sections for (p,n) reactions in $^{51}\text{V}$ and $^{113}\text{In}$:
5. Complete and Incomplete Fusion in $^{16}O + ^{169}Tm$ system: Measurements of recoil ranges:


6. Measurement and analysis of the cross-sections in $^{16}O + ^{159}Tb$ system below 7 MeV/nucleon:


7. Measurement and Analysis of Excitation Functions for Residues produced via Complete and Incomplete Fusion in $^{12}C + ^{128}Te$ system:


8. Decay of $^{177}Ta$ compound nucleus: Comparison of the excitation functions for the reaction residues occurring in $^{12}C + ^{165}Ho$ and $^{12}C + ^{163}Dy$ reactions:


95
9. A Study of Complete and Incomplete Fusion in Heavy Ion induced Reactions below 7 MeV/nucleon:
Manoj Kumar Sharma, Sunita Gupta, B.P. Singh, M.M. Musthafa, H.D. Bhardwaj and R.Prasad: International Conference on Nuclear Data for Science and Technology, Oct. 7-12, 2001, Tsukuba, Japan,

10. A Study of Complete, Incomplete Fusion and Pre-equilibrium Emission in Statistical Nuclear Reactions:

11. A Study of Incomplete Fusion in $^{12}C + ^{27}Al$ System below 7 MeV/nucleon:

12. Measurement and Analysis of Excitation Functions in Heavy Ion Induced Reaction:
13. Complete and Incomplete Fusion: Measurement of Recoil Range Distribution in $^{12}C + ^{165}Ho$ below 7 Mev/nucleon:

14. A Study of $^{16}O + ^{169}Tm$ system below 7 MeV/nucleon:

15. Measurement of Cross-sections for the Residue Produced via Incomplete Fusion of Oxygen with Natural Thulium:
MEASUREMENT OF RECOIL RANGES IN THE 
$^{12}$C + $^{165}$Ho SYSTEM BELOW 7 MeV/NUCLEON

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With a view to study complete (CF) and incomplete fusion (ICF) of $^{12}$C with $^{165}$Ho below 7 MeV/nucleon, the recoil range distribution of various evaporation residues formed in the interaction of $^{12}$C with $^{165}$Ho have been measured. In the case of $(C, xn)$ ($x = 3, 4, 5$) channels recoil range distributions show only one peak. Two distinct peaks, one having a lower mean value for range and another having a higher mean range (nearly the same as that for $(C, xn)$ channel) are observed in some cases. The two peaks in the recoil range distributions may be assigned, respectively, to the incomplete and completely fused systems.

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1. Introduction

The multiplicity of processes like complete fusion, incomplete fusion, direct transfer, etc., has made the study of the heavy ion reaction of considerable interest to nuclear physicists. The change in the mode of evolution of the heavy ion reaction with the variation in the incident beam energy, with entrance channel angular momentum, etc. are some of the topics of current interest.

There are various ways of classifying the different processes involved in heavy ion reactions. One of them is based on the degree of linear momentum transfer

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from the projectile to the composite system. In case of complete fusion, the entire linear momentum is transferred, while in case of incomplete fusion, only a part of the projectile fuses with the target (and the rest behaves as a spectator) leading to the fractional transfer of the incident momentum. The fraction of the momenta transferred in such cases depends on the mass of the fused fragment. Yet another process involves single nucleon/cluster transfer in a grazing collision. This process of direct reaction involves relatively less momentum transfer. Recoil velocities of the heavy residues, and hence their recoil ranges in a stopping medium can be used to determine the momentum transfer for individual channels. When the projectile fuses completely with the target, the composite system carries the entire linear momentum and hence travels a larger distance, while in the case when only a part of the projectile fuses with the target, the composite system travels a relatively smaller distance in the stopping medium and at an angle with respect to the incident direction. Previous studies\(^1\)\(^2\) show that incomplete fusion starts competing with complete fusion at energies above the Coulomb barrier. Several models like the break up fusion model, sum rule model, promptly emitted particles, exciton model, hot spot, etc., have been proposed to explain the incomplete fusion process.\(^3\)\(^-\)\(^6\) Because of the large angular momentum involved in the case of heavy ion reactions, a proper understanding of entrance channel partial waves is important in the study of incomplete fusion. In heavy ion reactions involving higher angular momentum, the compound nucleus formation is hindered due to the rapid rotation of the composite system which cannot exist as such and hence only a part of the projectile can fuse with the target. In terms of the partial waves, only a few lower partial waves contribute to complete fusion at higher angular momenta. The higher order partial waves contribute to incomplete fusion thereby reducing the complete fusion cross section.

Although particle-gamma coincidence studies\(^7\) and time of flight measurements of evaporation residues\(^8\) contribute a lot to the understanding of the mechanism of incomplete fusion processes, in a simple experiment, the individual contributions of complete and incomplete fusion can be separated by studying the recoil range distributions of various evaporation residues. In the recent past, such experiments have been carried out with medium mass nuclei targets\(^9\)\(^-\)\(^11\) with projectile energies as low as 7 MeV/nucleon. The calculations of angular momenta of fragments formed by incomplete fusion indicates the peripheral nature of collisions leading to incomplete fusion.\(^12\)

In this paper, the results of an experiment performed recently, at the Nuclear Science Center, New Delhi, India, are presented with a view to measuring the recoil range distributions of a number of evaporation residues formed in the interaction of \(^{12}\)C with \(^{165}\)Ho below 7 MeV/nucleon. This is an extension of our earlier experiment\(^13\) where the excitation functions for evaporation residues formed in the \(^{12}\)C + \(^{165}\)Ho system were measured below 7 MeV/nucleon. In this experiment, enhancement of experimentally measured cross-sections was observed in comparison to the theoretically calculated excitation functions for \((C, axn) (x = 2, 4, 6)\) and
Measurement of Recoil Ranges in the $^{12}\text{C} + ^{165}\text{Ho}$ System

$(C, 2axn) \ (x = 2, 4)$ emission products, indicating contributions from complete and incomplete fusion channels. It may be pointed out that the residues formed through the above mentioned channels may be produced by complete fusion as well as incomplete fusion processes. Thus, in order to separate the contribution of complete and incomplete fusion in the individual channels, in the present experiment, the recoil range distributions have been measured at two different incident lab energies, 71 and 80 MeV.

2. Experimental Details and Formulation

The experiment was carried out using the 15 UD Pelletron accelerator facility at the Nuclear Science Center, New Delhi, India. Aluminium-backed thin targets of Holmium (purity $> 99.9\%$) were prepared by the vacuum evaporation technique. The thickness of Ho deposition on the Aluminium backing was $\sim 200 \mu g/cm^2$. Thin aluminium catchers of different thicknesses were prepared by vacuum evaporation of Aluminium on glass slides and then floating the film on water. A stack of 13 catchers mounted on holders with concentric holes of diameter $\sim 1.2$ cm was used downstream of each target to trap the recoil products. A typical target catcher arrangement is shown in Fig. 1, where the recoiling nuclides are trapped in the stack of Aluminium catcher foils. The catcher thicknesses used in the experiment are given in Table 1.

The thickness of catchers and targets were measured individually prior to their use by the $\alpha$ transmission method, where the thickness is measured by determining the energy loss suffered by 5.486 MeV $\alpha$ particles from a $^{241}\text{Am}$ source while traversing through them. Stopping power tables of Northcliffe and Schilling\(^\text{14}\) were used to determine the sample and catcher thicknesses from the energy loss measurements. The targets with Aluminium backing facing the beam were irradiated with a $^{12}\text{C}$ beam in the GPSC (General Purpose Scattering Chamber) for a duration of about 24 hours each. The incident beam energies for the two irradiations were chosen in such a way that the beam hitting the Ho material had the desired

![Fig. 1. A typical target catcher arrangement used for measuring recoil range distributions.](image-url)
Table 1. The thicknesses of catcher foils used for 80 MeV and 71 Mev stacks.

<table>
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<tr>
<th>S. No</th>
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<th>Thickness in µg/cm² at energy 71 MeV</th>
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</tr>
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</table>

energy of 71 and 80 MeV, respectively. A beam current of ~ 38 nA behind the target catcher assembly was measured with an electron suppressed Faraday cup. The total beam fluence for each irradiation was also measured by a scalar integrator and was ~ 3500 µC. After the irradiation, the activities in each catcher foil were followed one by one off-line, for five days using a high resolution HPGe detector of 100 cm³ active volume of CANBERRA, coupled to CAMAC-based software, FREEDOM. The detector was pre-calibrated using a $^{152}$Eu source of known strength. The γ ray spectra were recorded using the ONLINE option of the FREEDOM software. The residues were identified by their characteristic γ radiations and half lives. The experimental cross-sections corresponding to the various radioactive residues in each catcher were computed by using the intensities of these γ rays in individual catchers. The half lives of the residual nuclei, characteristic γ ray energies, abundance, etc., are well established and are taken from the Table of Isotopes. The cross-sections for a particular residue in each catcher were obtained using

$$
\sigma_r(E) = \frac{A\lambda \exp(\lambda t_2)}{K_s N_0 \phi(G) [1 - \exp(-\lambda t_1)][1 - \exp(-\lambda t_3)]}
$$

where, $A$ is the observed counting rate of the induced activity of decay constant $\lambda$, $N_0$ the number of target nuclei irradiated for time $t_1$ with a particle beam of flux $\phi$, $t_2$ the time lapse between the end of irradiation and the start of counting, $t_3$ the data accumulation time, $\theta$ the branching ratio of the characteristic γ ray and $G\phi$ the geometry dependent efficiency of the detector. The factor $[1 - \exp(-\lambda t_1)]$ takes care of the decay of evaporation residue during the irradiation and is known as the saturation correction. The correction for the decay of the induced activity due to the delay between the end of irradiation and the start of counting and during the data
accumulation is taken into account via the factors \( \exp(\lambda t_2) \) and \( [1 - \exp(-\lambda t_3)] \), respectively. \( K_s \) is the correction for self absorption of radiation in the sample and is given by \( [(1 - \exp(-\mu d))/\mu d] \), where \( \mu \) is the \( \gamma \) ray absorption coefficient for a given energy in the material of the sample and \( d \) is the thickness of the sample.

To obtain the recoil range distributions, the measured cross section of each evaporation residue in an individual catcher was divided by the respective thickness of that catcher and plotted against the cumulative catcher thickness. The recoil range distributions were normalized using the cross section values measured by earlier experiment.

3. Results and Discussion

Differential recoil range distributions for various evaporation residues formed in the interaction of \(^{12}\)C with \(^{155}\)Ho at 71 and 80 MeV incident energy are shown in Figs. 2(a)-(i) and 3(a)-(i), respectively. The size of the squares include the errors in the experimental data. A detailed discussion about the various factors due to which errors may arise is given in one of our earlier publications. Dotted lines guide the eye to the experimental data. As can be seen from the figures, at a given value of incident energy, the recoil range distributions for Ta and Hf isotopes (i.e. \((C, x\alpha n)\) and \((C, pxn)\) \(x\) being an integer) channels, respectively) have a peak at only one value of cumulative catcher thickness. However, for most of the Lu and Tm isotopes (i.e. \((C, xn)\) and \((C, pxn)\) channels, respectively) either two peaks or only one peak at a relatively lower value of cumulative catcher thickness have been observed. The Recoil range distributions for the Ta and Hf isotopes are nearly Gaussian, peaked at a depth nearly corresponding to the expected recoil range of the \(^{177}\)Ta nucleus \((\sim 400-500 \mu g/cm^2)\), calculated using the classical approach and the stopping power tables of Northcliffe and Schilling, meaning thereby that these products are formed by the complete fusion process only, followed by the evaporation of \(n\) and/or \(p\). The recoil range distributions for \((C, x\alpha n)\) \(x = 2, 4, 6\) evaporation residues peak at two values of cumulative catcher thickness, one corresponding to the complete fusion \((\sim 400-500 \mu g/cm^2)\) and the other at a lower value of range \((\sim 200-300 \mu g/cm^2)\). This indicates that these products are populated not only by the complete fusion process, but also by some other process in which the linear momentum transfer is less than that for complete fusion process. This is possible when only a part of the projectile fuses with the target (incomplete fusion) and the rest of it goes with a velocity nearly equal to the velocity of the projectile. The two peaks in the range distributions indicate that the products are also partly formed by incomplete fusion. In some of the cases corresponding to \((C, 2x\alpha n)\) \(x = 2, 4\) channels there is only one peak at a value of the mean range which is considerably lower than the value expected for complete fusion. In these cases, the residues are probably only formed by the process of incomplete fusion.

As a representative case, in order to separate the relative contributions of complete and incomplete fusion in the \((C, \alpha 4n)\) channel at 80 MeV, the two peaks in
Fig. 2. Experimentally measured recoil range distributions for various evaporation residues formed in the interaction of $^{12}$C with $^{16}$O at 71 MeV.

- (a) $E_{c.m.} = 21.0$ MeV
- (b) $E_{c.m.} = 21.0$ MeV
- (c) $E_{c.m.} = 21.0$ MeV
- (d) $E_{c.m.} = 21.0$ MeV
- (e) $E_{c.m.} = 21.0$ MeV
- (f) $E_{c.m.} = 21.0$ MeV
- (g) $E_{c.m.} = 21.0$ MeV
- (h) $E_{c.m.} = 21.0$ MeV
- (i) $E_{c.m.} = 21.0$ MeV
- (j) $E_{c.m.} = 21.0$ MeV
Fig. 3. Experimentally measured recoil range distributions for various evaporation residues formed in the interaction of $^{12}$C with $^{165}$Ho at 80 MeV.
Fig. 4. (a) Gaussian fit to the recoil range distribution data for reaction \( (C, \alpha 4n) \) at 80 MeV. (b) Gaussian fit to the recoil range distribution data for reaction \( (C, \alpha 4n) \) at 71 MeV.

the recoil range distributions were fitted with a Gaussian distribution (Fig. 4(a)) and their areas were computed. The relative contribution of the two processes are obtained by dividing the area of the corresponding peak by the total area. The incomplete fusion contribution in this case is found to be 72% with an uncertainty of 5%. The total contribution of incomplete fusion, which is the cumulative sum of ICFs for various channels observed in the present experiment is found to be \( \sim 17\% \) with an uncertainty of 5% at these energies. However, for the same reaction at 71 MeV the recoil range distribution shows only one peak which may be fitted with a Gaussian distribution as shown in Fig. 4(b). This may indicate that at 71 MeV the reaction is by complete fusion only.

4. Conclusions

Recoil range distributions for nine different evaporation residues formed in the reaction \( ^{12}\text{C} + ^{165}\text{Ho} \) have been measured at energies below 7 MeV/nucleon. Single and/or double peaks in the recoil range distributions have been observed. These peaks may be assigned to the complete and incomplete fusion of \( ^{12}\text{C} \). The relative contributions of incomplete and complete fusion channels have been separated and it has been found that incomplete fusion contribution is \( \sim 17\% \) with an uncertainty of 5% at these energies.
References


Decay of $^{177}\text{T}_a$ Composite Nucleus: Comparison of Excitation Functions for the Reaction Residues Occurring in $^{12}\text{C} + ^{165}\text{Ho}$ and $^{14}\text{N} + ^{163}\text{Dy}$ Reactions

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The experiment has been performed with a view to studying complete and incomplete fusion in $^{14}\text{N} + ^{163}\text{Dy}$ system below 7 MeV/nucleon. The excitation functions for several reactions have been measured using the activation technique and compared with the theoretical predictions based on statistical models. The codes ALICE-91 and CASCADE used earlier for the analysis of excitation functions in case of $^{12}\text{C} + ^{165}\text{Ho}$ system have been used here also with the same set of input parameters. It has been observed that the theoretical calculations do not match with the experimental excitation functions well but the overall shape of the excitation function is reproduced satisfactorily. The composite nucleus ($^{177}\text{T}_a$) formed in this ($^{14}\text{N} + ^{163}\text{Dy}$) case is the same as the one formed in $^{12}\text{C} + ^{165}\text{Ho}$ system studied earlier. Measured excitation functions for the same decay channels in the two cases (i.e. $^{12}\text{C} + ^{165}\text{Ho}$, and $^{14}\text{N} + ^{163}\text{Dy}$) have been compared. A comparison of these excitation functions indicates relatively smaller values of cross sections for all reactions in $^{14}\text{N} + ^{163}\text{Dy}$, in general. Moreover, it has been found that in contrast to the $^{12}\text{C}$ induced reactions, where a substantial part of the reaction cross section goes through incomplete fusion, there is no contribution from incomplete fusion to the reaction cross section in the case of $^{14}\text{N}$ induced reactions at these energies. This may indicate that $^{12}\text{C}$ undergoes breakup into $^4\text{He}$ and $^8\text{Be}$, while $^{14}\text{N}$ does not undergo breakup below 7 MeV/nucleon.

KEYWORDS: heavy ions, excitation functions, compound nucleus, composite system, activation

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1. Introduction

In the heavy ion induced reactions, the study of breakup of heavy ions followed by the fusion of one of the fragments with the target has been of great interest. Even at energies slightly above the Coulomb barrier, incomplete fusion starts competing with complete fusion.$^{1,3,5}$ Recent studies report breakup of $^{12}\text{C}$ and $^{16}\text{O}$ into $^4\text{He}$ and $^8\text{Be}$ fragments and their incomplete fusion with the target.$^{5}$

Ghoshal$^3$ in his experiments showed that same compound nucleus formed by proton and $\alpha$ as projectiles decay similarly, thus indicating the validity of the Bohr compound nucleus assumption. In the last four decades, some experiments that are extension of Ghoshal's experiment have been done to compare proton induced reactions with heavy ion induced reactions leading to the same composite system.$^6$ In the case of proton and heavy ion induced reactions, it has been found that, if one plots the cross sections for a particular channel populated via two different entrance channels as a function of excitation energy, there is a difference because of the different Coulomb barriers in the two cases. Similar experiments have been done with two heavy ions, $^{12}\text{C}$ and $^{16}\text{O}$, where the complete and incomplete fusion of $^{12}\text{C}$ and $^{16}\text{O}$ in medium mass nuclei have been studied by recoil range measurements of reaction residues. The present experiment has been done with a view to studying breakup of $^{14}\text{N}$ in reactions below 7 MeV/nucleon and to comparing the excitation functions for $^{12}\text{C}$ and $^{14}\text{N}$ induced reactions leading to the same composite system (in the present case $^{177}\text{T}_a$). Activation technique has been used to measure excitation functions for the production of various isotopes in the interaction of $^{14}\text{N}$ with $^{163}\text{Dy}$. The results of the experiment performed with the $^{12}\text{C} + ^{165}\text{Ho}$ system have been presented in ref. 1. In the present paper, the results of the experiment performed with the $^{14}\text{N} + ^{163}\text{Dy}$ system are presented. The presently measured excitation functions have been compared with theoretical calculations based on statistical model codes, ALICE-91 and CASCADE. The code ALICE-91 takes into account pre-equilibrium emission together with compound nucleus calculations. To look for pre-equilibrium emission, if any, in the case of $^{14}\text{N} + ^{163}\text{Dy}$ reaction products, theoretical calculations have been done using the code ALICE-91. It may be noted that the code ALICE-91 is based on Weisskopf-Ewing model which does not take into account the angular momentum involved in the heavy ion induced reactions. On the other hand, the code CASCADE is based on the Hauser-Feshbach theory which takes into account the angular momentum effects. Thus, in order to look for pre-equilibrium emission, if any, and also to see the effect of angular momentum, calculations using two different codes have been performed. Further, the excitation functions for same reaction residues populated in the two reactions have been compared.

2. Formalism and Experimental Details

Reaction cross sections for several reactions induced by $^{14}\text{N}$ ions on $^{163}\text{Dy}$ have been measured using activation technique. The experiment has been carried out at the Nuclear Science Center (NSC), New Delhi, India, using the Pelletron accelerator facility. The $^{163}\text{Dy}$ samples were
prepared by vacuum evaporation of enriched Dysprosium on Aluminium backing. Composite thickness of $^{13}A_i + ^{163}D_y$ was measured by α-transmission method. The thickness of the Aluminium backing was separately measured before Dysprosium deposition, by the same method and was ~0.3 mg/cm$^2$. Assuming the backing to be uniform, its thickness was subtracted from the composite thickness of $^{13}A_i + ^{163}D_y$ sample. The calibrated $^{241}Am$ α-source was used for these measurements. The thickness of $^{163}D_y$ material was ~0.5 mg/cm$^2$. As a check, the target thicknesses were also measured with the quartz thickness monitor and they were found to agree with each other within 5%. The Aluminium catcher foils of thicknesses 6.75 mg/cm$^2$ kept just behind the target were used to collect the residues recolling out of the target.

The $^{163}D_y$ samples were irradiated with $^{14}N$ beam at energies 65, 70, 75 and 84 MeV of beam currents ≈6 to 18 nA and of charge state 5$^+$/6$^+$. Each irradiation was performed for about 3 hours duration in the General Purpose Scattering Chamber (GPSC) having invacuum transfer facility. The beam flux was monitored by the charge collected in the Faraday cup using an ORTEC current integrator device.

Pre-calibrated high-resolution (2 keV for 1.33 MeV γ ray of $^{60}Co$) HPGe detector of 100 cm$^3$ active volume coupled to the ORTEC’s PC-based multichannel analyzer was used to follow the activities induced in the irradiated samples off line. The detector was calibrated using the standard $^{152}Eu$ point source of known strength which emits γ rays over a wide range of energy (121 keV to 1408 keV). Following formula was used for computing the geometry dependent efficiency ($G_e$) of the detector at a particular energy

$$G_e = \frac{N_o}{N_o e^{(-\lambda)t} + J^*},$$ \hspace{1cm} (1)

where $N_o$ is the disintegration rate of the standard γ source at the time of measurement, $N_o$ is the disintegration rate at the time of manufacture, $\lambda$ is the decay constant, $t$ is the time lapse between the manufacture of the source and the start of counting, $J^*$ is the branching ratio of the characteristic γ ray.

After the irradiation, the activities induced in the samples were followed off-line. The γ ray spectra were recorded for 3 days at increasing times. Typical γ ray spectra for $^{12}C + ^{163}H_o$ system at 71 MeV and $^{14}N + ^{163}D_y$ at 70 MeV are shown in Figs. 1 and 2, respectively. Notice that the channel number vs. energy calibration is different for $^{12}C + ^{163}H_o$ and $^{14}N + ^{163}D_y$ systems. As can be seen directly from the two spectra, the peaks corresponding to incomplete fusion channels, e.g., 739.83 keV of $^{171}Lu$, 191.21 keV of $^{169}Lu$, 239.14 keV of $^{157}Lu$, 207.79 keV of $^{157}Tm$ and 218.79 keV of $^{157}Tm$ are observed in $^{12}C + ^{163}H_o$ spectrum, while they are absent in $^{14}N + ^{163}D_y$ spectrum. The residues were identified by their characteristic γ radiations and half-lives. In some cases, where the gamma rays of residual nuclei have energies close to each other (e.g. $^{174}Ta$, $T_{1/2} = 1.18$h, $E_\gamma = 206.38$ keV and $^{167}Tm$; $T_{1/2} = 9.24d$, $E_\gamma = 207.79$ keV), their individual contributions were separated from the analysis of decay curves on the basis of their half-lives. In the above example, no contribution from $^{167}Tm$ has been observed. Because of the low/interfering activities induced in the sample, counts recorded from the MCA were plotted explicitly as a function of channel number using the program ORIGIN and the area under different peaks were determined by Gaussian fitting. In the present measurements, the count rates determined from that area have been used to calculate the experimental cross sections corresponding to the various radioactive residues. The half-lives of the residual nuclei, characteristic γ ray energies, abundance etc., are taken from the Table of Radioactive Isotopes and are given in Table I.

At a given beam energy ($E$) in the lab frame, the experimental reaction cross sections $\sigma_e(E)$ for different reaction residues have been calculated using the following formula:

$$\sigma_e(E) = \frac{\lambda \exp(\lambda t_2)}{K_e N_0 \phi(G_e)} [1 - \exp(-\lambda t_1)][1 - \exp(-\lambda t_3)].$$ \hspace{1cm} (2)

### Table I. Radioactive properties of reaction residues with their prominent γ rays identified in the experiment.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>$J^*$</th>
<th>$E_\gamma$ (keV)</th>
<th>Abundance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{71}P_{25}\text{a}$</td>
<td>1.18$h$</td>
<td>3$^+$</td>
<td>206.38</td>
<td>57.70</td>
</tr>
<tr>
<td>$^{75}P_{38}\text{d}$</td>
<td>3.65$h$</td>
<td>5/2$^-$</td>
<td>172.19</td>
<td>17.00</td>
</tr>
<tr>
<td>$^{75}F_{27}\text{d}$</td>
<td>36.8$m$</td>
<td>3$^+$</td>
<td>213.96</td>
<td>52.00</td>
</tr>
<tr>
<td>$^{12}H_{25}$</td>
<td>1109.23</td>
<td></td>
<td></td>
<td>14.00</td>
</tr>
<tr>
<td>$^{78}H_{25}$</td>
<td>23.6$h$</td>
<td>1/2$^-$</td>
<td>123.67</td>
<td>83.00</td>
</tr>
</tbody>
</table>
where A is the observed counting rate of the induced activity of decay constant λ, N₀ the number of target nuclei irradiated for time t₁ with a particle beam of flux φ, t₂ the time lapse between the stop of irradiation and the start of counting, t₃ the data accumulation time, θ the branching ratio of the characteristic γ ray and Gᵣ the geometry dependent efficiency of the detector. The factor \[1 - \exp(-\lambda t₁)\] takes care of the decay of evaporation residue during the irradiation and is typically known as the saturation correction. The correction 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 is taken into account via the factors \[\exp(\lambda t₂)\] and \[1 - \exp(-\lambda t₃)\], respectively. Kᵣ is the correction for self absorption of radiation in the sample and is given by \[[1 - \exp(-\mu d)]/\mu d\], where, \μ is the γ ray absorption coefficient for the material of the sample and \(d\) is the thickness of the sample. Further details of the experimental technique etc. are discussed in ref. 1.

3. Results and Discussion

In the present experiment, excitation functions for the reactions \(^{163}D_y(N, 3n)\)\(^{174}Ta\), \(^{163}D_y(N, A₄)\)\(^{173}Ta\), \(^{163}D_y(N, S₅)\)\(^{172}Ta\) and \(^{163}D_y(N, p3n)\)\(^{172}Hf\) have been measured using the activation technique. The measured cross sections for these reactions are tabulated in Table II. Errors in the measured cross sections arise mostly from the detector efficiency, solid angle effect, target thickness, counting statistics and intensity measurements, and have been discussed in details in ref. 1. Due to thin target samples and lower beam intensities, the induced activities and hence the observed count rates were quite small and therefore subjected to somewhat larger errors.

Complete fusion of \(^{14}N\) with \(^{163}D_y\) followed by the emission of one or more neutrons lead to the production of \(^{163}Ta\) isotopes, while the emission of a proton and one or more neutrons lead to the production of \(^{163}Hf\) isotopes. The \(\beta^+\) decay or electron capture (EC) of higher charge precursor \(^{163}Ta\) isobar may also produce \(^{163}Hf\) isotopes. In the case of evaluating the cross section for \((N, p3n)\) channel no precursor contribution has been subtracted since the counting was done for relatively small duration.

Theoretical calculations have been done with codes ALICE-91\(^9\) and CASCADE.\(^10\) The code ALICE-91 employs Weisskopf-Ewing model\(^11\) for compound nucleus calculations and Hybrid model\(^12\) for pre-equilibrium calculations. The code assumes equipartition of energy among the initial excited particles and holes. Out of the many input parameters in the code, initial exciton number \(n_{_{\text{ix}}}\), mean free path multiplier COST and level density parameter \(a (= A/K)\), where A is the atomic mass of the compound system) are quite important. The parameter \(n_{_{\text{ix}}}\) and COST largely govern pre-equilibrium contribution, while the parameter \(a\) governs mainly the equilibrium component. The initial exciton number \(n_{_{\text{ix}}}\) decides the complexity of the initial configuration and a higher value of \(n_{_{\text{ix}}}\) is likely to reduce the contribution of pre-equilibrium emission, if any. In the case of \(^{12}C + \(^{163}H_{_{\text{a}}}\) system, assuming that at these incident energies, the incident \(^{12}C\) ion breaks up in the field of the nucleus and the nucleons occupy excited states above the Fermi energy, \(n_{_{\text{ix}}} = 12\) was taken and the agreement of the theoretical predictions with the experimentally measured excitation functions was found to be satisfactory. On the same reasoning, \(n_{_{\text{ix}}} = 14\) has been taken for \(^{14}N + \(^{163}D_y\) system, but surprisingly, in the later case, the agreement is not satisfactory. In the present calculations \(n_{_{\text{ix}}}\) has been taken as 14 (\(n_{_{\text{ix}}} = 7, n_{_{\text{st}}} = 7, n_{_{\text{h}}} = 0\)), COST = 3 and the level density parameter constant \(K\) has been taken as 9.5. All other parameters were kept same as the ones taken in case of \(^{12}C + \(^{163}H_{_{\text{a}}}\) system.\(^11\)

Since heavy ion induced reactions involve large angular momenta, and the angular momentum effects are not included in Weisskopf-Ewing model calculations, the excitation functions have been shifted by an amount approximately equal to \(E_{_{\text{rot}}} ~ (m/M)E_{_{\text{lab}}}\), where \(m/M\) is the ratio of the projectile and target masses and \(E_{_{\text{lab}}}\) is the incident energy. The reason for shifting the calculated excitation functions and the procedure have been discussed in detail elsewhere.\(^1\) The experimental and calculated excitation functions are shown in Fig. 3.

The code CASCADE employs Hauser-Feshbach theory\(^13\) for cross section calculations. Theoretical calculations have been performed consistently using the same set of parameters as in case of \(^{12}C + \(^{163}H_{_{\text{a}}}\) system. An important parameter in the code CASCADE is \(F_{_{\text{g}}},\) which is defined as the ratio of the actual moment of inertia to the rigid-body moment of inertia of the excited system. It has been observed that the calculations done with the default value of

<table>
<thead>
<tr>
<th>(E_{_{\text{lab}}}) (MeV)</th>
<th>(\sigma(14^{Ta})) (mb)</th>
<th>(\sigma(17^{Ta})) (mb)</th>
<th>(\sigma(17^{Ta})) (mb)</th>
<th>(\sigma(17^{Hf})) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>65.0 ± 0.3</td>
<td>~</td>
<td>3.0 ± 0.8</td>
<td>~</td>
<td>5.0 ± 1.1</td>
</tr>
<tr>
<td>70.0 ± 0.5</td>
<td>0.9 ± 0.2</td>
<td>8.1 ± 1.8</td>
<td>40.2 ± 13.0</td>
<td>11.2 ± 1.7</td>
</tr>
<tr>
<td>75.0 ± 0.1</td>
<td>2.3 ± 1.0</td>
<td>74.8 ± 15.5</td>
<td>415.8 ± 78.2</td>
<td>41.0 ± 7.8</td>
</tr>
<tr>
<td>84.0 ± 0.3</td>
<td>~</td>
<td>30.5 ± 6.7</td>
<td>156.7 ± 31.7</td>
<td>27.2 ± 8.1</td>
</tr>
</tbody>
</table>

Table II. Experimentally measured cross sections for various reaction residues produced in the reaction \(^{14}N + \(^{163}D_y\)\) at different incident lab energies.

Fig. 3. Excitation functions for \(^{163}D_y(N, 3n)\)\(^{174}Ta\), \(^{163}D_y(N, A₄)\)\(^{173}Ta\), \(^{163}D_y(N, S₅)\)\(^{172}Ta\) and \(^{163}D_y(N, p3n)\)\(^{172}Hf\) reactions. Theoretical predictions of the code ALICE-91 for \(^{174}Ta\), \(^{173}Ta\), \(^{172}Ta\) and \(^{173}Hf\) are shown by dot, solid, dash-dot and dash-dot-dot curves, respectively.
the parameter $F_0 = 0.85$ does not reproduce the experimentally measured excitation functions in this case also. The excitation functions calculated with different values of $F_0$ are shown in Fig. 4. As may be seen from this figure, no value of the parameter $F_0$ reproduces the measured excitation functions over the whole range of energy, however, $F_0 = 0.30$ gives a better representation of experimental data, in general. This anomalous value of the parameter $F_0$ may be due to the fact that in case of heavy ion induced reactions, the angular momentum imparted to the composite system is large and hence it deviates considerably from rigid body configuration leading to such an anomalous value of parameter $F_0$. The calculated excitation functions for $(N,3n)$ channel underestimate the measured excitation functions. This may be due to the contribution of higher charge isobar precursor $^{174}T_a$ to the measured cross section, which could not be separated. In theoretical calculations, fission channel has also been included but is found to have negligible effect on the calculated excitation functions.

It may be noted that in the present measurements for $^{14}N + {^{163}}D_y$ system incomplete fusion channels like $(N,\alpha x n)$ and $(N,2\alpha x n)$ have not been observed, while in the case of $^{12}C + {^{163}}H_o$ system enhanced cross sections for $(C,\alpha x n)$ and $(C,2\alpha x n)$ channels were observed, though the same composite system is produced in the two cases at the nearly same excitation energies. As such, it may be an indication that $^{12}C$ undergoes break up into $^4H_o$ and $^8B_p$ while there is no break up of $^{14}N$ at these energies to give rise to incomplete fusion.

As has already been mentioned, the same composite system $^{177}T_a$ was populated via two different entrance channels, viz., $^{14}N + {^{163}}D_y$ and $^{12}C + {^{163}}H_o$, at nearly same excitation energies. The measured cross sections for different decay channels in these two cases are compared in Fig. 5. Lines are drawn through the experimental points to guide the eyes. A comparison of these excitation functions indicates relatively smaller values of cross sections, in general, for all the reactions in $^{14}N + {^{163}}D_y$. Smaller cross section for the same exit channel in the case of $^{14}N$ induced reactions is largely due to the large value of Coulomb barrier $(U_c)$ for $^{14}N + {^{163}}D_y$ system $(U_c \approx 70 \text{ MeV})$ as compared to the $^{12}C + {^{163}}H_o$ system $(U_c \approx 51 \text{ MeV})$. As such, the measurements in the case of $^{14}N$ induced reactions are generally below the Coulomb barrier, while in $^{12}C$ induced reactions they are mostly above the Coulomb barrier. In order to illustrate this point, calculated cross sections for the formation of compound nucleus $^{4}TeC^{16}O$ and $^{4}Tc^{14}N$ for the carbon and nitrogen induced systems are plotted against the difference of the center of mass energy $E_{cm}$ to the Coulomb barrier $U_c$ in Fig. 6. At minimum incident lab energies the calculated value of $(E_{cm} - U_c)$ for $^{12}C + {^{163}}H_o$ system is $-0.4 \text{ MeV}$ and for $^{14}N + {^{163}}D_y$ system is $-10.5 \text{ MeV}$. 

![Fig. 4. Excitation functions for $^{163}D_y(N,3n)^{174}T_a$, $^{163}D_y(N,4n)^{173}T_a$, $^{163}D_y(N,5n)^{172}T_a$ and $^{163}D_y(N,p3n)^{173}H_o$ reactions. The filled circles represent the experimental data. The theoretical predictions of the code CASCADE with $F_0 = 0.15$, $F_0 = 0.30$ and $F_0 = 0.85$ (default value) are represented by solid, dash-dot-dot and dotted lines, respectively.](image)

![Fig. 5. $^{12}C$ and $^{14}N$ induced reaction cross sections as a function of the excitation energy of the compound nucleus. Solid, dash-dot, dash-dot-dot and dotted lines are drawn to guide the eye for the experimental data of 3n, 4n, 5n and p3n channels, respectively.](image)

![Fig. 6. Calculated cross sections for the formation of compound nucleus $^{4}TeC^{16}O$ and $^{4}Tc^{14}N$ for the carbon and nitrogen induced systems plotted against the difference of the center of mass energy $E_{cm}$ to the Coulomb barrier $U_c$.](image)
Further, the maximum value of \((E_{CM} - U_e)\) is approximately 21 MeV and 6 MeV respectively for \(^{12}C + ^{163}Ho\) and \(^{14}N + ^{163}Dy\) systems. As such, in the case of \(^{14}N\) induced reactions, measurements are done at energies below the Coulomb barrier, where \(\sigma_{c}(^{14}N)\) is much lower and varies rapidly with energy. It may be noted that below the Coulomb barrier, a change of about 5 MeV on the energy axis changes \(\sigma_{c}(^{14}N)\) by a factor of 100. Further, the angular momentum distribution involved in the two cases is also different. At nearly the same excitation energies, e.g., 71 MeV \(^{12}C\) beam and 70 MeV \(^{14}N\) beam (excitation energy \(\approx 53\) MeV), the orbital angular momentum in the incident nitrogen beam is higher than \(^{12}C\) beam by 4\(^\text{th}\).

4. Conclusion

Excitation functions for the reaction residues produced in \(^{14}N + ^{163}Dy\) reaction have been measured by using off beam spectrometry. These have been compared with the excitation functions for the same reaction residues produced in \(^{12}C + ^{165}Ho\). In the present analysis, the contributions from incomplete fusion channels for \(^{14}N\) induced reactions have not been observed. It may be an indication that \(^{14}N\) does not undergo breakup below 7 MeV/nucleon. Moreover, the comparison of excitation functions for the two systems indicates that, in general, the cross sections for \(^{12}C\) induced reactions are higher than \(^{14}N\) induced reactions. This may be due to the fact that even at nearly the same excitation energies, the angular momentum distribution involved in the two cases are different and also the Coulomb barriers for the two systems are different. It appears that in case of heavy ion induced reactions, the effect of angular momentum and Coulomb barriers in the entrance channel becomes significant in determining the decay modes of the composite system, as expected.

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5) S. N. Ghoshal; Phys. Rev. 80 (1950) 939.
13) W. Hauser and H. Feshbach; Phys. Rev. 87 (1952) 366.
Complete and Incomplete Fusion: Measurement and Analysis of Excitation Functions in $^{12}$C+$^{128}$Te system at energies near and above the Coulomb barrier

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Abstract: In order to study complete and incomplete fusion in heavy ion induced reactions the experiment has been carried out for measuring excitation functions (EF's) for several reactions in the system $^{12}$C+$^{128}$Te, in the energy range ≈42-82 MeV, using activation technique. To the best of our knowledge EF's for presently measured reactions are being reported for the first time. The measured EF's have been compared with those calculated theoretically using codes CASCADE and ALICE-91. Effect of variation of parameters of the codes on calculated EF's has also been studied. The analysis of the present data indicates presence of contributions from incomplete fusion in some cases. In general, theoretical calculations agree well with the experimental data.

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I. INTRODUCTION

In the past few decades energetic heavy ion (HI) beams have been used to study the reaction mechanism in complex nuclei. In case of medium energy HI reactions, one expects the interplay between the compound nucleus and direct reaction processes along with the pre-equilibrium (PE) emission. The important experimental signatures of PE emission are i) the presence of larger number of high energy particles as compared to the spectrum predicted by compound nucleus theory and ii) slowly decreasing tails of the excitation functions. The HI reactions may be understood in terms of an interaction potential between the centre of mass of the two colliding nuclei consisting of a repulsive Coulomb, short range attractive nuclear and centrifugal potentials. Such reactions have provided a unique way of populating and studying a system of nucleons under extreme degrees of freedom such as angular momentum and excitation energy. At energies from around the Coulomb barrier to well above it, the complete fusion (CF) and incomplete fusion (ICF) reactions, along with PE-emission have been found to have significant contribution in HI induced reactions[1-4]. In case of CF the incident projectile fuses with the target nucleus to form a compound nucleus, while, in case of ICF only a part of the projectile fuses with the target nucleus and the rest moves in the beam direction with almost the same velocity as that of incident ion beam.

In order to study the reaction mechanism in light and heavy ion induced reactions a program of precise measurement and analysis of EF's in a large number of systems has been undertaken. Measurement of a large number of EF's of reactions induced by light ions (proton and α-particles) have already been reported elsewhere[5-9]. In the present work the EF's for the reactions \(^{128}\text{Te} (^{12}\text{C},3n)^{131m}\text{Ce}\). \(^{128}\text{Te} (^{12}\text{C},5n)^{125}\text{Ce}\). \(^{128}\text{Te} (^{12}\text{C},p4n)^{135}\text{La}\). \(^{128}\text{Te} (^{12}\text{C},α3n)^{133m}\text{Ba}\). \(^{128}\text{Te} (^{12}\text{C},α5n)^{131}\text{Ba}\). and
$^{128}$Te($^{12}$C,$\alpha$4pn)$^{131m}$Te measured in the energy range =42-82 MeV. using activation technique have been presented. The experiment has been performed at the Nuclear Science Centre (NSC), New Delhi, India. The analysis of the measured EF's has been carried out using the computer codes CASCADE[10] and ALICE-91[11]. The code CASCADE performs pure statistical calculations while the code ALICE-91 takes compound nucleus as well as PE-emission into account. Comparison of experimentally measured EF's with theoretical calculations indicates, in some cases, contribution to the reaction cross-sections from ICF also. The comparison of experimental data with ALICE-91 calculation has also indicated significant contribution from PE-emission at higher energies. It may, however, be pointed out that these codes do not take ICF into consideration. Details of the experiment are given in section II, while the analysis of the data is given in section III of this paper.

II. EXPERIMENTAL

The experiment has been carried out at the NSC, New Delhi, India. In the present work stacked foil activation technique has been used for measuring the EF's. Further details of the experiment are given in this section.

A. Sample preparation

The samples of enriched isotopes of $^{128}$Te (87%) were prepared by vacuum evaporation technique. The $^{128}$Te material was deposited on the Aluminum (Al) foils of thickness 6.75 mg/cm$^2$. The thickness of the samples was measured by determining the energy loss suffered by 5.486 MeV $\alpha$-particles from $^{241}$Am source while traversing through the target material. The measured thickness of the $^{128}$Te deposition was found to be $\approx$0.92 mg/cm$^2$. In the present case the Al backing served
as energy degrader as well as backing material. The samples were pasted on aluminum holders having concentric holes of 10 mm diameter. Al-holders were used for rapid heat dissipation and for keeping identical geometries for irradiation and counting.

**B. Irradiation**

A stack of four samples prepared as mentioned above was irradiated by $^{12}\text{C}^{5+}$ beam of energy 82 MeV obtained from the 15 UD Pelletron accelerator at the NSC, New Delhi, India. The irradiation was performed in the General Purpose Scattering Chamber (GPSC), having in-vacuum transfer facility. The samples in stack were arranged such that the $^{128}\text{Te}$ material faced the beam, so that the recoiling nuclei may be trapped in the Al backing. The stack was irradiated for nearly six hours keeping in view the half-lives of interest. Beam current of $\approx 10$ pNA behind the target assembly was measured with an electron suppressed Faraday cup. The total beam fluence was found to be 1253 $\mu$C. The incident energy of $^{12}\text{C}$ beam on each foil in the stack was calculated from the energy degradation of the initial beam energy using the stopping power values of $^{12}\text{C}$-ion in Te and Al materials from the tables of Northcliffe and Schilling [12].

**C. Formulation**

If $N_0$ numbers of target nuclei are irradiated by the beam of flux $\phi$, then the cross-section $\sigma$, for the product nuclei of interest may be given by.

$$\sigma = \frac{[A \lambda \exp(\lambda t)]}{[N_0 \phi \mathcal{K}_a(G) \times \{1 - \exp(-\lambda t)\} \{1 - \exp(-\lambda t)\}]}$$
Where, $A$ is the total count accumulated in time $t_n$, $\lambda$ is decay constant for residual nucleus, $t_i$ is the time of irradiation, $t_i$ is the time elapsed between stop of irradiation and start of counting. $G_e$ is the geometry dependent efficiency of the detector. $\theta$ is the branching ratio of characteristic $\gamma$-rays and $K_o$ is the correction term due to self absorption of $\gamma$-radiation.

**D. Measurement**

The activities induced in the irradiated samples were followed for about a week using High Purity Germanium (HPGe) detector of 100 c.c. active volume coupled to a PC through CAMAC based FREEDOM software[13]. The sample-detector distance for the counting was adjusted depending on the intensity of the induced activities so that dead time of counting is always <10%. Proper correction for dead time is taken into account. The HPGe detector (resolution 2 keV for 1.33 MeV $\gamma$-ray of $^{60}$Co) was pre-calibrated using various standard sources like $^{22}$Na, $^{54}$Mn, $^{57}$Co, $^{133}$Ba, $^{137}$Cs and $^{152}$Eu at different source-detector separations. The geometry dependent efficiencies at various source-detector distances were measured using $^{152}$Eu source. A typical geometry dependent efficiency curve as a function of the $\gamma$-ray energy is shown in Fig. 1. The residues produced in various reactions were identified by their characteristic $\gamma$-rays and half-lives. The $\gamma$-ray spectrum of each irradiated foil was recorded at increasing times and analysed in order to identify the photo-peaks of the interest. Typical $\gamma$-ray spectra of $^{128}$Te irradiated by $^{12}$C$^{5-}$ ion at 70.8 MeV and 82.0 MeV are shown in Figs. 2 and 3, respectively. In some cases the same residual nucleus may be populated through more than one reaction channels i.e., by the activation due to irradiation and also by the decay of a
higher charge isobar precursor nucleus through $\beta^-$ emission or electron capture. In such cases, the intensity of characteristic $\gamma$-rays has contributions from all such channels. For such cases, the cumulative cross-section has been determined. Radioactive properties of various residues produced by different reactions are given in Table 1.

Experimentally measured cross-sections at different energies for the reactions $^{128}\text{Te}(^{12}\text{C,3n})^{137}\text{mCe}$, $^{128}\text{Te}(^{12}\text{C,5n})^{135}\text{Ce}$, $^{128}\text{Te}(^{12}\text{C,p4n})^{135}\text{La}$, $^{128}\text{Te}(^{12}\text{C,α3n})^{133}\text{mBa}$, $^{128}\text{Te}(^{12}\text{C,α5n})^{131}\text{Ba}$, and $^{128}\text{Te}(^{12}\text{C,α4pn})^{131}\text{mTe}$ are given in Table 2. The errors mentioned in the cross-section values are the overall errors due to several factors as given in the following.

E. Uncertainty in Measurements

Each experiment may have some uncertainty in its measurements. Some of the factors likely to introduce errors in the present measurements are given below.

1. Uncertainty in determining the geometry dependent detector efficiency. The statistical errors of the counting of the standard sources may give rise to the error in efficiency, which was minimised by accumulating large number of the counts for comparatively larger times (~5000-7000 sec). Experimental data on the variation of geometry dependent efficiencies with the $\gamma$-ray energy at a fixed source-detector distance has been fitted with power law curve. The uncertainty due to fitting of the efficiency curve is estimated to be $< 3\%$. Uncertainty in determining the efficiency may also come up due to the solid angle effect, because the irradiated samples were not point sources like standard source, but they had a diameter of ~4
A detailed analysis of the solid angle effect is given in reference [14]. It is estimated that the error in the efficiency on account of solid angle effect is < 6%.

(2) There may be uncertainty in determining the number of target nuclei in sample due to inaccurate estimate of the foil thickness and non-uniform deposition of the target material. It is estimated from the thickness measurements at different locations of the same sample that error due to non-uniform deposition is expected to be < 1%.

(3) Error may come up due to fluctuations in beam current during the irradiation. Although, care was taken to keep the beam current constant within 10%. It is estimated that beam fluctuations may introduce an error of < 3%.

(4) During irradiation of the stack, the beam traverses the thickness of the material, thus the initial beam intensity reduces. It is estimated that the error due to decrease in beam intensity is expected to be < 2%.

(5) In all these measurements the dead time is kept less than 10% by suitably adjusting the sample-detector distance and the corrections for it was applied in the counting rate.

Further, the uncertainties in the branching ratio, decay constant etc., which are taken from Nuclear Data Tables. Data sheets and Table of Isotopes etc., have not been taken into account.

III. RESULTS AND DISCUSSION

With the view of studying the CF and ICF of heavy ions, EF’s for six reactions induced in $^{12}$C+$^{128}$Te system have been measured in the energy range $\approx$42.2 to 82.0
The EF's for \( ^{128}\text{Te}(^{12}\text{C},3n)^{137m}\text{Ce} \), \( ^{128}\text{Te}(^{12}\text{C},5n)^{135}\text{Ce} \), \( ^{128}\text{Te}(^{12}\text{C},4p4n)^{135}\text{La} \), \( ^{128}\text{Te}(^{12}\text{C},\alpha3n)^{133m}\text{Ba} \), \( ^{128}\text{Te}(^{12}\text{C},\alpha5n)^{131}\text{Ba} \) and \( ^{128}\text{Te}(^{12}\text{C},\alpha4pn)^{131m}\text{Te} \) reactions have been measured using the activation technique and calculated using statistical model codes. To the best of our knowledge EF's for these reactions are being reported for the first time. The Coulomb barrier for the system \(^{12}\text{C}+^{128}\text{Te}\) is \( \approx 40.2 \text{ MeV} \). Experimentally measured and theoretically calculated EF's for all the reactions measured presently are given in Figs. 4-9. The vertical error bars in the experimental data represent the overall errors in the measured cross-section values as discussed in section II.E of this paper. The size of the circle includes the uncertainty in the incident energy. A detailed description of the models and computer codes is given elsewhere[15], however, for the sake of completeness brief details of the codes used are given in the following parts.

A. Analysis

The analyses of EF's have been performed using two different computer codes viz., CASCADE[10] and ALICE-91[11]. The code CASCADE is purely statistical in nature, while the code ALICE-91 includes PE-emission also. However, ICF is not considered in calculations done by both these codes. Further details of calculation and the parameters involved are discussed in the following parts for each code respectively.

1. Analysis with code CASCADE

The code CASCADE[10] is based on Hauser-Feshbach theory[16] and does not consider the possibility of ICF and/or PE-emission. In this code the level density parameter \( a \) of the compound system, the ratio of actual moment of inertia of the
excited system to the rigid body moment of inertia $F_\theta$ and level density parameter at
the saddle point $a_f$ are some of the important parameters. The transmission
coefficients in these calculations are generated using the optical model potentials of
Becchetti and Greenlees[17] for neutrons and protons and that of Satchler[18] for $\alpha$-
particles. Fermi gas model is used in this code to calculate the level density
parameter $a$ for the product nuclei. using the expression $a=\Lambda/K$, where, $\Lambda$ is the
atomic mass number and $K$ is the parameter. The default value of $K$ is 10. however, in
the present work, the calculations have been done by varying the values of $K$, from
10 to 14. The effect of variation in the values of $K$ on the calculated EF’s is shown in
Figs. 4. As can be observed from these figures, $K=14$ is found to reproduce the data
satisfactorily in general. The value of parameter $F_\theta$ has been varied from 0.55 to its
default value 0.85. The effect of variation in parameter $F_\theta$ on calculated EF’s is also
shown in Figs. 5, and is found to have negligible effect on calculated EF’s for
reactions under investigation. This code also takes into account fission channel. The
level density parameter $a_f$ at the saddle point may be obtained from the relation
$a_f=\Lambda/D_{AF}$, where, $\Lambda$ is the mass number of the nucleus and $D_{AF}$ is a parameter whose
default value is equal to 8. The parameter $D_{AF}$ is found to influence the calculated
EF’s considerably. As such the influence of variation of $D_{AF}$ from 8 to 11 on
calculated EF’s has also been studied. The resulting EF’s using these values of
parameters $D_{AF}=(8-11)$. $K=14$ and $F_\theta=0.55$ are shown in Figs. 6. A value of $D_{AF}=11$
gives a good agreement, in general with experimental data even in the peak region. As
can be seen from these figures that the EF’s for reactions $^{128}$Te($^{12}$C,3n)$^{137m}$Ce,
$^{128}$Te($^{12}$C,5n)$^{135}$Ce and $^{128}$Te($^{12}$C,4n)$^{135}$La are qualitatively in good agreement with
theoretical calculations done with code CASCADE in the peak region. The higher
values of experimental cross-sections in the tail portion of EF for reaction
\(^{128}\text{Te}(^{12}\text{C}\cdot 3n)^{137m}\text{Ce}\) (Fig. 6a) as compared to the theoretical calculations may be attributed to the PE-emission which is dominant mode of reaction at higher energies and is not considered in the CASCADE calculations. In case of \(^{128}\text{Te}(^{12}\text{C}\cdot 5n)\) channel the experimental data is satisfactorily reproduced by CASCADE calculations as is indicated in Fig. 6(b). This indicates that at 82 MeV excitation energy, there is negligible contribution from PE emission in (C.5n) channel. This is expected as PE emission is more likely in the first step of de-excitation and leaves the residual system in an excited state from where emission of 4 neutrons is less likely. However, the emission of 2 neutrons leading to (C.3n) channel is quite possible. It may, however, be pointed out the PE-emission in (C.5n) channel may appear at still higher excitation energies. The calculations done for the reactions \(^{128}\text{Te}(^{12}\text{C}\cdot 3n)^{132m}\text{Ba}\) and \(^{128}\text{Te}(^{12}\text{C}\cdot 5n)^{131}\text{Ba}\) are not in good agreement with experimentally measured EF's. they reproduce only the qualitative trend of the measured EF's. One of the plausible reason for this discrepancy may be the large contribution of ICF in these cases. In Fig. 4(f), the calculations done using code CASCADE are not plotted as theoretical calculations give cross-section values less than 0.1mb at energies of interest for the reaction \(^{128}\text{Te}(^{12}\text{C}\cdot 4pn)^{131}\text{Te}\). It may indicate that ICF is the dominant mode of reactions for this channel at these energies.

2. Analysis with Code ALICE-91

The code ALICE-91[11] has been developed by M. Blann. to account for the equilibrium (CN) as well as PE-emission in light and heavy ion reactions. The CN calculations in this code are performed using Weisskopf-Ewing model, while PE component is simulated using Hybrid/Geometry Dependent Hybrid model[19]. In this code the level density parameter \(a\), initial exciton number \(n_0\) and the mean free path
multiplier $COST$ are some of the important parameters. The level density parameter $a$ mainly affects the equilibrium component, while the initial exciton number $n_0$ and mean free path multiplier $COST$ govern the PE-component. The level density parameter $a$ is calculated from the expression $a = A/K$, where $K$ is a parameter which may be varied to match the experimental data. Calculations have been performed with different values of these parameters. The effect of variation of the parameter $K$ on calculated EF's is presented in Figs. 7. As can be seen from these figures, in the present calculations, a value of $K = 18$ and $COST = 2$, in general, satisfactorily reproduce the experimental data for all the reactions.

In the hybrid model the intermediate states of the system are characterised 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. It is of particular interest to look for the initial exciton number required to reproduce the data. In order to see the effect of variation in the values of the initial exciton number $n_0$, on calculated EF's, calculations for different initial exciton configurations were performed. As a representative case, these calculations for the reactions $^{128}$Te($^{12}$C,3n)$^{137m}$Ce, and $^{128}$Te($^{12}$C,α3n)$^{133m}$Ba for $n_0 = 12$ ($6p - 6n + 0h$) and $n_0 = 14$ ($6p + 7n + 1h$) are shown in Figs. 8, respectively. It may be seen from these figures that lower value of initial exciton number, in general, gives larger PE contributions as expected. It is because of the fact that lower value of $n_0$ means larger number of two-body interactions prior to the establishment of equilibrium characteristic of CN resulting in larger PE contribution. Further, it has been found that the parameter $COST$ does not influence the calculated EF's considerably. As a representative case the
effect of variation of parameter $COST$ on the calculated EF for the reaction $^{128}\text{Te}(^{12}\text{C},3n)^{137}\text{mCe}$ is shown in Fig.9.

Further, it may be pointed out that the maxima of the measured EF's were found to peak at energies higher than the corresponding calculated EF's. This is expected, since in ALICE-91 calculations the angular momentum effects have not been taken into account. In HI induced reactions incident particle imparts relatively larger angular momentum to the composite system. If, in the last stages of nuclear de-excitation, higher angular momentum inhibits particle emission more than it does $\gamma$ emission, then, the peak of EF's corresponding to the particle emission mode will be shifted to higher energies[20]. The effect is more pronounced in HI reactions as compared to the light ion reactions, since the rotational energy is much greater in case of HI reactions. An estimate of the possible shift due to angular momentum effects may be made from the nuclear rotational energy $E_{rot}$. For a rigid body moment of inertia $E_{rot}=(m/M)E_{lab}$, where $m/M$ is the ratio of the projectile and the target nucleus masses and $E_{lab}$ being incident energy[20]. In the present case at incident energies 42.2 to 82 MeV, the rotational energies vary from 3.9 to 7.7 MeV. Since the angular momentum effects have not been considered in the Weisskopf-Ewing calculations of present version of code ALICE-91, it is desirable to shift the calculated EF's by the amount approximately equal to $E_{rot}$ as calculated above. It has been observed that the ALICE-91 calculations satisfactorily reproduce the experimental data when the energy scale of the calculated excitation functions are shifted by respective $E_{rot}$ values. The enhancement of cross-sections in the measured EF's for the reactions $^{128}\text{Te}(^{12}\text{C},5n)^{133}\text{mBa}$, $^{128}\text{Te}(^{12}\text{C},5n)^{131}\text{Ba}$ and $^{128}\text{Te}(^{12}\text{C},4pn)^{131}\text{mTe}$, in general, as compared to the theoretical predictions can be attributed to the fact that these channels may be populated not only by the CF of $^{12}\text{C}$ but also may have a significant
contribution of ICF of $^8$Be or $\alpha$ of $^{12}$C with $^{128}$Te. It may, however, be noted that for 
$^{128}$Te($^{12}$C,$\alpha$3n)$^{133m}$Ba reaction, measured cross-section value at energy $\approx$42.2 MeV is larger than what is predicted by the calculations. At present we can not assign any specific reason for this.

The reaction $^{128}$Te($^{12}$C,3n) produces residual isotope $^{137}$Ce which has both the ground ($t_{1/2}$=9h) as well as metastable state ($t_{1/2}$=1.43d). The metastable state $^{137m}$Ce decays to ground state by the emission of 254.2 keV (11%) $\gamma$-ray. Since, the $^{137}$Ce emits $\gamma$-ray of very low intensities, it could not be observed. As such, contribution of only metastable state $^{137m}$Ce has been measured. In the present case the residue $^{135}$La may be produced independently via the reaction ($^{12}$C,p4n) and the same residue ($^{135}$La) may also be produced by $\beta^-$ decay of its higher charge isobar precursor ($^{135}$Ce) produced via ($^{12}$C,5n) reaction. The independent yield of $^{135}$La could not be measured in the present analysis because the half-lives of the residue $^{135}$La and its precursor $^{135}$Ce are not very much different (19.8 h and 17.7 h respectively). However, in such cases, formulations developed in reference[21] may be followed, according to which the ratio of the activities of the parent ($^{135}$Ce) and the daughter ($^{135}$La) having nearly same half-lives would increase linearly for some time. Using these formulations, the yield of $^{135}$La via the precursor decay of $^{135}$Ce has been found to be less than 1 mb at 82 MeV. The experimentally measured cross-sections for the reaction ($^{12}$C,p4n) contain the contribution of precursor decay also. The reaction $^{128}$Te($^{12}$C,$\alpha$4pn) produces both the ground state $^{131}$Te ($t_{1/2}$ =25 min) as well as isomeric state $^{131m}$Te ($t_{1/2}$ =1.2 d). The isomeric state decays to ground state. Since, the counting of the irradiated samples was started after considerable delay due to the high activity of the samples, the $^{131}$Te ground state contribution could not be separated for ($^{12}$C,$\alpha$4pn) reaction.
IV. Conclusions

In the present analysis EF's for six reactions have been measured and compared with theoretical predictions based on codes CASCADE and ALICE-91. In general, satisfactory agreement with experimental data and theoretical calculations is obtained with proper choice of parameters. The high energy part of the excitation function for the reaction $^{128}$Te($^{12}$C,3n)$^{137m}$Ce could be satisfactorily reproduced by theoretical calculations only by code ALICE-91, which takes into account PE-emission. The high energy region of ($^{12}$C,3n) EF could not be reproduced by codes CASCADE as in this code PE-emission has not been taken into account. Further, the EF's for the reaction channels which may have contribution from ICF also are generally not satisfactorily reproduced by theoretical calculations because these codes do not consider ICF into account. The discrepancy between experimental and theoretical calculations may be partly attributed to the ICF. From the comparison of experimental data with theoretical calculations, it may be inferred that reaction $^{128}$Te($^{12}$C,α4pn)$^{131m}$Te takes place mostly via ICF only. It may, however, be pointed out that the residual nucleus $^{131m}$Te produced in this reaction may also be populated via deep inelastic collision from $^{130}$Te isotope which is present in the target because of 87% enrichment of $^{128}$Te. The relative abundance of $^{130}$Te isotope is expected to be ≈6% and since deep inelastic collision is likely to dominate at higher incident energies, the contribution from deep inelastic collision is expected to be very low. As such most of the measured cross-section from the reaction $^{128}$Te($^{12}$C,α4pn)$^{131m}$Te is likely to be due to ICF. It may be pointed out that the relative contributions of CF and ICF could not be separated from the present analysis. However, this separation may be done by measuring the recoil range distribution (RRD) of residues produced in CF and ICF reactions.
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References:


(1991) 146.


[13] FREEDOM Software for data acquisition: Developed by NSC. New
Delhi, India (2000).


Table Captions

Table 1: Radioactive properties of residues identified.

Table 2: Measured cross-sections for production of residual isotopes in \( ^{12}C + ^{128}Te \) system.
**Figure Captions**

**Fig. 1** Typical geometry dependent efficiency as a function of $\gamma$-ray energy.

**Fig. 2** Typical $\gamma$-ray spectrum of $^{129}$Te irradiated by $^{12}$C$^{5+}$ ions at incident energy 70.8 MeV.

**Fig. 3** Typical $\gamma$-ray spectrum of $^{129}$Te irradiated by $^{12}$C$^{5+}$ ions at incident energy 80.0 MeV.

**Figs. 4** Experimentally measured and theoretically calculated excitation functions using code CASCADE. Effect of variation of level density parameter constant (K) on calculated excitation function with $F_0=0.65$ and $D_{AF}=8$ is also shown in these figures.

**Figs. 5** Experimentally measured and theoretically calculated excitation functions using code CASCADE. Effect of variation of parameter $F_0$ on calculated excitation function with $K=14$ and $D_{AF}=8$ is also shown in these figures.

**Figs. 6** Experimentally measured and theoretically calculated excitation functions using code CASCADE. Effect of variation of parameter $D_{AF}$ on calculated excitation function with $K=14$ and $F_0=0.65$ is also shown in these figures.

**Figs. 7** Experimentally measured and theoretically calculated excitation functions using code ALICE-91. Effect of variation of level density parameter (K) on calculated excitation function with initial exciton number $n_0=12$ and mean free path multiplier COST=2 is also shown in these figures.
Figs. 8 Experimentally measured and theoretically calculated excitation functions using code ALICE-91. Effect of variation of parameter $n_0$ on calculated excitation function with $K=18$ and mean free path multiplier $COST=2$ is also shown in these figures.

Fig. 9 Experimentally measured and theoretically calculated excitation functions using code ALICE-91. Effect of variation of parameter $COST$ on calculated excitation function with $K=18$ and $n_0=12$ is also shown in these figures.
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<td>82.0±0.9</td>
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<td>292.7±32.0</td>
<td>82.4±9.1</td>
<td>37.6±4.2</td>
</tr>
</tbody>
</table>
Fig. 1
Figs. 5

(a) $^{126}$Te$(C,3n)^{135}$Ce

(b) $^{126}$Te$(C,5n)^{135}$Ce

(c) $^{126}$Te$(C,p4n)^{135}$La

(d) $^{126}$Te$(C,α3n)^{133}$Ba
Figs. 6
Figs. 8
Fig. 9

$^{128}$Te(C,3n)$^{137m}$Ce

Energy (MeV)

$\sigma$(mb)