STUDY OF ANGULAR AND RECOIL RANGE DISTRIBUTIONS FOR SOME RESIDUES PRODUCED IN HEAVY ION REACTIONS

ABSTRACT

THESIS
SUBMITTED FOR THE AWARD OF THE DEGREE OF
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UNDER THE SUPERVISION OF
PROF. R. PRASAD

DEPARTMENT OF PHYSICS
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Abstract

Atomic nucleus, which is the central part of the atom is a very complex system. Nucleons are the basic building blocks of the nucleus and display both single particle and collective motions. The force, which holds these nucleons within the nucleus is naturally very complex and has no classical analog. One of the basic aims of research in low energy nuclear physics is to get information about the nuclear forces and structure of the nucleus. One way of getting this information is through the study of nuclear reactions.

A nuclear reaction is said to occur when target and the projectile nuclei/nuclear particles come close to each other within the range of nuclear force. A large variety of nuclear reactions may be represented by the following binary equation;

$$\begin{array}{ccc}
\text{z}_a \text{ } A_a \text{ } + \text{z}_X \text{ } A_X & \rightarrow \text{z}_Y \text{ } A_Y \text{ } + \text{z}_b \text{ } A_b \\
\end{array}$$

(1)

In this equation $A_a z_a$ is the projectile which, may be a nuclear particle or a nucleus and $A_X z_X$ is the target nucleus. $A_Y z_Y$ and $A_b z_b$ are the residual nucleus and the ejectile, respectively. In a nuclear reaction, all the parameters of the system are known, before and after the reaction has taken place. What happens during the nuclear reaction is not well understood. It is because of the very short time ($\approx 10^{-22}$ to $10^{-15}$ sec) involved in nuclear reactions. Since, the exact process of a nuclear reaction is not well known, therefore, simplified theories and models are developed for explaining the mechanism of the nuclear
reaction. Neils Bohr proposed first such model for nuclear reactions in the year 1936[1] called the compound nucleus (CN) reaction model. Although, the CN model was proposed to explain observed resonances in thermal and low energy neutron cross-sections, but the concept was extended to reactions at higher energies invoking the random phase approximation.

According to CN model, a nuclear reaction proceeds in two steps. The first step is the formation of the compound nucleus and the second step is its decay. Both these steps are assumed to be independent of each other. In the formation of CN, incident projectile fuses with the target nucleus and forms a composite system. In the composite system, angular momentum and energy carried by the projectile are shared with all the nucleons of the system randomly and after a certain time thermodynamic equilibrium is established. The expected time for the formation of the equilibrated compound nucleus is \(\approx 10^{-16}\) sec. Once the equilibrium is established, the CN forgets its history of formation and then decays by the emission of light particles or nuclides and/or \(\gamma\)-rays.

The second kind of approach, in order to describe the nuclear reaction, is the direct reaction mechanism. In direct reactions, only a few degrees of freedom are excited. Direct reactions may further be sub-divided into three categories, viz., (1) Knock-out reactions, where the incident particle hits a nucleon or a cluster of nucleons at the surface of the target nucleus which is then ejected. (2) Pick-up reactions, where the incident particle picks up nucleon/nucleons from the target, and (3) Stripping reactions, where, the incident projectile loses one or few nucleons, which are absorbed by the target
nucleus. Such reactions are likely to occur at considerably higher excitation
energies. Both the intuition and the results of some recent measurements
indicated the presence of reaction processes, which are intermediate between
these two extreme reaction mechanisms. In CN mechanism it is assumed
that the thermodynamic equilibrium of the compound nucleus is achieved
by a series of two body residual interactions between the nucleons of the
composite system. The CN so formed decays only after the attainment of
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With the availability of accelerated beams of heavy ions (HIs), the study
of nuclear reactions initiated by HI has acquired central place in nuclear
physics research. Heavy ions may be distinguished from the light ions in
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This makes the study of HI reactions more complex because the projectile
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semiclassical approach, one considers radial motion of ions classically and
angular motion in central force field quantum mechanically. In case of elastic scattering process projectile and target are the same, they do not lose their identity, while in the deep inelastic, transfer and fusion reactions both the projectile and the target lose their identity. Semiclassical description of HI reactions is possible in terms of the distance of closest approach \( r_{\text{min}} \), which is related to the impact parameter \( b \) by the relation[3],

\[
 r_{\text{min}} = \frac{b}{\sqrt{1 - \frac{V(r_{\text{min}})}{E_{\text{CM}}}}} \tag{2}
\]

Where, \( V(r_{\text{min}}) \) is the nuclear potential between the target and projectile, and \( E_{\text{cm}} \) is the center of mass energy of the projectile. Some of the important processes that may occur in HI interactions are given below:

(i) Rutherford scattering or Coulomb excitation in the region \( r_{\text{min}} > R_N \).
(ii) Deep inelastic scattering and incomplete fusion peripheral with region \( R_F < r_{\text{min}} \leq R_{\text{Dic}} \).
(iii) Transfer reactions around the region with \( R_{\text{Dic}} < r_{\text{min}} \leq R_N \).
(iv) Fusion reactions are confined within the region \( 0 \leq r_{\text{min}} \leq R_F \).

Here, \( R_N \) is the grazing range of nuclear force. \( R_{\text{Dic}} \) and \( R_F \) \( \approx 1.0(A_1^{1/3} + A_2^{1/3}) \) are the minimum distances for the deep inelastic collision and fusion, respectively.

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 com-
pound nucleus. In general, the total cross-section for these reactions may be
estimated as,

\[ \sigma = \pi R^2 = \pi \lambda^2 \ell^2 \] (3)

The cross-sections for fusion and for deep inelastic scattering may be repre-
sented by using the equation (3) as ;

\[ \sigma_{DIC} = \pi \lambda^2 (\ell_{DIC}^2 - \ell_F^2), \] (4)

\[ \sigma_F = \pi \lambda^2 \ell_F^2, \] (5)

The partial reaction cross-section for such a collision at a given energy \( E \)
may be given by [3],

\[ \sigma_{\ell}^R(E) = \pi \lambda^2 (2\ell + 1)T_{\ell}(E) \] (6)

Where, \( T_{\ell}(E) \) is the transmission coefficient of the \( \ell^{th} \) partial wave for the
potential \( V_\ell(r) \) at energy \( E \). \( \ell_F \) and \( \ell_{DIC} \) are the orbital angular momentum
for the HI interactions (fusion and deep inelastic scattering). In the 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 ex-
plained by the effective potential depending on distance and relative angular
momentum having the form,

\[ V_\ell(r) = V_c(r) + V_n(r) + V_{cent}(r) \] (7)

\[ \sigma_{\ell}^R(E) = \pi \lambda^2 (2\ell + 1)T_{\ell}(E) \] (8)
Where, $V_c(r)$ is the repulsive Coulomb potential and is given by,

$$V_c(r) = \frac{1}{4\pi\varepsilon_0} \frac{Z_P \ Z_T \ e^2}{r} \quad (9)$$

for $r \geq R_c$

$$V_c(r) = \frac{1}{4\pi\varepsilon_0} \frac{Z_P \ Z_T \ e^2}{2R_c} (3 - \frac{r^2}{R_c^2}) \quad (10)$$

for $r \leq R_c$.

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

$$V_n(r) = \frac{V_o}{1 + \exp\left(\frac{r-R}{a}\right)} \quad (11)$$

where,

$$R = r_o(A_{T}^{1/3} + A_{P}^{1/3}) \quad (12)$$

and

$V_{cent}(r)$ is the repulsive centrifugal potential given by,

$$V_{cent}(r) = \frac{\hbar^2 \ell(\ell + 1)}{2\mu r^2} \quad (13)$$

Here, $Z_P$ and $Z_T$ 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), $\ell$ the angular momentum and $\mu$ the reduced mass of the interacting nuclei. $V_o$ is the depth of the potential, $a$ the diffuseness parameter and $r_o=1.31 \ \text{fm}$. It may further be pointed out that at low energies and larger impact parameters, when the two ions pass through each other at distances larger than the range of
the nuclear interaction, they interact only through their Coulomb fields and elastic scattering may take place as only $V_c$ and $V_{cent}$ are important. For grazing impact parameter $b_{gr}$, processes like inelastic scattering and nucleon transfer may take place. This may be due to the overlapping of the tails of nuclear wave functions. On further reduction of impact parameter, the wave functions of the two interacting nuclei overlap considerably and a part of the relative kinetic energy may be converted into internal excitation before the two separates into target and projectile like systems. These deep inelastic collisions take place at energies of the order of few $MeV/A$ above the Coulomb barrier. At still lower values of impact parameter the two ions may come within the range of nuclear interactions and may fuse. Classically, nuclear interactions can 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 nucleus and a number of nuclear reactions may take place. At lower incident energies and for smaller values of impact parameters, the incident projectile may completely fuse with the target nucleus resulting in the formation, first of a composite system which, may undergo thermal equilibration to become a compound nucleus, PE-emission may take place during the equilibration of the composite system. Such kind of process is termed as complete fusion (CF). If only a part of projectile fuses with the target nucleus and the remaining part of it moves on in the beam direction with almost the same velocity as that of incident ion, the process is termed as incomplete fusion (ICF)[4, 5, 6, 7]. There are various ways of classifying these processes. One of them is based on the
degree of linear momentum transferred from the incident projectile to the composite system. In case of CF, the entire linear momentum of the projectile is transferred to the composite system, while in case of ICF, only a part of projectile fuses with the target nucleus leading to the fractional transfer of linear momentum\[8, 9, 10, 11\]. The fraction of momentum transferred depends on the mass of the fused fragment\[12, 13\].

Though, several methods are available to study the reaction mechanism, however information of considerable value may be extracted from the measurement and analysis of excitation functions (EFs), recoil range distributions and angular distributions of the residues produced in HI interaction. In the HI reactions, the final state has a heavy residual nucleus, light ions and/or \( \gamma \) rays. In most of the experiments the properties like, charge, mass, energy, 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 \( \gamma \) rays, if radioactive, and by measuring their half lives.

Activation technique is one of the simplest but powerful methods of measuring the excitation functions and to deduce important information about the nuclear reaction mechanism. In this technique, the activities induced in the target and catcher assembly are measured off line. The main advantage
of the activation technique is the possibility of measuring cross-sections for the production of a large number of residues in a single irradiation thereby reducing beam-time requirements. Activation method is a very important method and is often used for the measurement of the reaction cross-sections.

In the HI reactions, at moderate energies a large number of reaction channels are open and the analysis of EFs for these reactions may provide significant information about the CF, ICF and PE emission. The slowly descending tail of the EFs is one of the important signatures of PE emission. Vergani et al.,[5] have measured the EFs for the production of a large number of isotopes in the interaction of \(^{12}\text{C}\) with \(^{197}\text{Au}\) 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 HI 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 limited and no systematic study has been done so far. In order to have a better understanding of these processes, more experimental data covering a wide range of projectile-target pairs over entire periodic table and energy is required. In the case of CF entire linear momentum of the projectile is transferred to the target nucleus, the composite system recoils in the beam direction to a larger distance. However, in case of ICF depending on the mass of the fused fragment, relatively low momentum is transferred to the target and the residue recoils at distances that become increasingly smaller with the decreasing mass of the fused projectile fragment. As such,
information regarding the relative contribution of CF and ICF in HI reactions may be extracted from the analysis of recoil range measurements of the residues. Some earlier studies[7, 8, 9, 10, 12, 15] 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 5 MeV/nucleon. A significant contribution of ICF to the total reaction cross-section has been observed in these studies.

In this work, as part of a program[13, 15, 16, 17] to study CF, ICF and PE emission in HI induced reactions, activation technique has been used to measure the EFs for several reactions in $^{14}N + ^{128}Te$, $^{16}O + ^{103}Rh$ and $^{16}O + ^{130}Te$ systems at energies near and well above the Coulomb barrier. A list of these reactions is given below:

$^{128}Te^{(14N, 4n)^{136m}Pr}$, $^{128}Te^{(14N, 5n)^{137}Pr}$, $^{128}Te^{(14N, p4n)^{137}Ce}$,

$^{128}Te^{(14N, α5n)^{133}La}$, $^{128}Te^{(14N, α6n)^{132}La}$, $^{128}Te^{(14N, α2pn)^{135m}Cs}$,

$^{128}Te^{(14N, 2α2pn)^{131}I}$, $^{128}Te^{(14N, 3α)^{130}I}$, $^{128}Te^{(14N, p4n)^{137}Ce}$,

$^{103}Rh^{(16O, p2n)^{116}Te}$, $^{103}Rh^{(16O, 2p)^{117}Sb}$, $^{103}Rh^{(16O, 2pn)^{116}Te}$,

$^{103}Rh^{(16O, 2η)^{115}Sb}$, $^{103}Rh^{(16O, α)^{115}Sb}$, $^{103}Rh^{(16O, 2α)^{115}In}$,

$^{103}Rh^{(16O, 2α2n)^{109}I}$, $^{103}Rh^{(16O, 3α)^{106m}Ag}$, $^{103}Rh^{(16O, 3α3n)^{104}Ag}$,

$^{130}Te^{(16O, 5n)^{141}Nd}$, $^{130}Te^{(16O, α3n)^{139}Ce}$, $^{130}Te^{(16O, 3αn)^{133}Xe}$,

$^{130Te^{(16O, 3αn)^{133m}Xe}}$ and $^{130Te^{(16O, 3α3n)^{131m}Xe}}$.

The analysis of EFs has been performed employing three different computer codes viz., ALICE-91[19], PACE[20] and CASCADE[21]. The experiments have been carried out using the HI beams obtained from the Pelletron
accelerator at the Inter University Accelerator Centre (IUAC), New Delhi, India. The calculations of cross-sections for some ICF Channels in the system \(^{16}O + ^{169}Tm\) at 81 \(\text{MeV}\) incident energy have been done using the SUMRULE\([22]\) model.

Further, to study the energy dependence and to separate out the relative contributions of CF and ICF in \(^{16}O + ^{169}Tm\) system, the RRDs of several residues have been measured at \(\approx 76\) and 81 \(\text{MeV}\). The RRD for the radioactive residues of reactions \(^{169}Tm(^{16}O, 3n)\^{182}Ir\), \(^{169}Tm(^{16}O, p3n)\^{183}Os\), \(^{169}Tm(^{16}O, p2n)\^{182}Os\), \(^{169}Tm(^{16}O, p3n)\^{181}Os\), \(^{169}Tm(^{16}O, \alpha)\^{181}Re\), \(^{169}Tm(^{16}O, 2\alpha pn)\^{178}Hf\), \(^{169}Tm(^{16}O, 2\alpha p5n)\^{171}Hf\), \(^{169}Tm(^{16}O, 3\alpha n)\^{172}Lu\) and \(^{169}Tm(^{16}O, 3\alpha 2n)\^{171}g\ Lu\) have been measured. An attempt has also been made to measure the angular distributions of some radioactive residues populated in the reactions \(^{169}Tm(^{16}O, 3n)\^{182}Ir\), \(^{169}Tm(^{16}O, 4n)\^{181}Ir\), \(^{169}Tm(^{16}O, p2n)\^{182}Os\), \(^{169}Tm(^{16}O, p3n)\^{181}g\ Os\), \(^{169}Tm(^{16}O, \alpha)\^{181}g\ Re\) and \(^{169}Tm(^{16}O, 3\alpha n)\^{172}g\ Lu\) at \(\approx 81\ \text{MeV}\) incident beam energy. Analysis of the measured data has indicated significant contribution from incomplete fusion for several reaction channels. Details of the experiments and analysis are presented in the following chapters of the thesis.
References


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To my mother

Smt. Shashi Bala Varshney

M.A. (Hindi, Economics), B.Ed. IGD
CERTIFICATE

Certified that the work presented in this thesis is the original work of Ms. Unnati done under my supervision.

Prof. R. Prasad
Professor of Experimental Nuclear Physics
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Chapter 1

INTRODUCTION
Atomic nucleus, which is the central part of the atom is a very complex system. Nucleons are the basic building blocks of the nucleus and display both single particle and collective motions. The force, which holds these nucleons within the nucleus is naturally very complex and has no classical analog. One of the basic aims of research in low energy nuclear physics is to get information about the nuclear forces and structure of the nucleus. One way of getting this information is through the study of nuclear reactions.

A nuclear reaction is said to occur when target and the projectile nuclei/nuclear particles come close to each other within the range of nuclear force. A large variety of nuclear reactions may be represented by the following binary equation;

\[ \frac{A_a}{Z_a} a + \frac{A_X}{Z_X} X \rightarrow \frac{A_Y}{Z_Y} Y + \frac{A_b}{Z_b} b \quad (1) \]

In this equation $\frac{A_a}{Z_a} a$ is the projectile which, may be a nuclear particle or a nucleus and $\frac{A_X}{Z_X} X$ is the target nucleus. $\frac{A_Y}{Z_Y} Y$ and $\frac{A_b}{Z_b} b$ are the residual nucleus and the ejectile, respectively. In a nuclear reaction, all the parameters of the system are known, before and after the reaction has taken place. What happens during the nuclear reaction is not well understood. It is because of the very short time ($\approx 10^{-22}$ to $10^{-16}$ sec) involved in nuclear reactions. Since, the exact process of a nuclear reaction is not well known, therefore, simplified theories and models are developed for explaining the mechanism of the nuclear reaction. Neils Bohr proposed first such model for nuclear reactions in the year 1936[1] called the compound nucleus (CN) reaction model. Although,
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The second kind of approach, in order to describe the nuclear reaction, is the direct reaction mechanism. In direct reactions, only few degrees of freedom are excited. Direct reactions may further be sub-divided into three categories, viz., (1) Knock-out reactions, where the incident particle hits a nucleon or a cluster of nucleons at the surface of the target nucleus which is then ejected. (2) Pick-up reactions, where the incident particle picks up nucleon/nucleons from the target, and (3) Stripping reactions, where, the incident projectile loses one or few nucleons, which are absorbed by the target nucleus. Such reactions are likely to occur at considerably higher excitation
energies. Both the intuition and the results of some recent measurements indicated the presence of reaction processes, which are intermediate between these two extreme reaction mechanisms.

Fig. 1.1 A SCHEMATIC REPRESENTATION OF THE FORMATION AND DECAY OF THE COMPOUND NUCLEUS AND PRE-EQUILIBRIUM EMISSION IN NUCLEAR REACTIONS.
In CN mechanism it is assumed that the thermodynamic equilibrium of the compound nucleus is achieved by a series of two body residual interactions between the nucleons of the composite system. The CN so formed decays only after the attainment of equilibrium. However, it is possible that particle emission takes place from each successive intermediated state, even before the establishment of equilibrium. The particles which, are emitted during equilibration are called pre equilibrium particles and reaction mechanism as pre equilibrium (PE) emission. As such, PE emission serves as a bridge between the direct and the compound reaction mechanisms.

With the availability of accelerated beams of heavy ions (HIs), the study of nuclear reactions initiated by HI has acquired central place in nuclear physics research. Heavy ions may be distinguished from the light ions in many ways. The charge and mass of heavy ions are larger than light ions, thus energy and momentum carried by the heavy ions are relatively large. This makes the study of HI reactions more complex because the projectile and target nuclei both are many body quantum systems and large amount of energy and angular momenta are involved. Since, the de-Broglie wavelength \( \lambda \), involved in HI reactions is small compared to the radius of the target nucleus, one can treat HI reactions in semiclassical approach\[2, 3\]. In semiclassical approach, one considers radial motion of ions classically and angular motion in central force field quantum mechanically. A pictorial representation of HI interaction is shown in Fig. 1.2[2]. In case of elastic scattering process projectile and target are the very same, they do not lose their identity, while in the deep inelastic, transfer and fusion reactions both the projectile
and the target lose their identity. Semiclassical description of HI reactions is possible in terms of the distance of closest approach $r_{\text{min}}$, which is related to the impact parameter $b$ by the relation\(^{(2)}\),

$$r_{\text{min}} = \frac{b}{\sqrt{1 - \frac{V(r_{\text{min}})}{E_{\text{cm}}}}} \tag{2}$$

Where, $V(r_{\text{min}})$ is the nuclear potential between the target and projectile, and $E_{\text{cm}}$ is the center of mass energy of the projectile. Some of the important processes that may occur in HI interactions are given below;

(i) Rutherford scattering or Coulomb excitation in the region $r_{\text{min}} > R_N$. 

\hspace{1cm}Fig. 1.2 PICTORIAL REPRESENTATION OF A HEAVY ION INTERACTION
(ii) Deep inelastic scattering and incomplete fusion peripheral with region $R_F < r_{\text{min}} \leq R_{\text{Dic}}$.

(iii) Transfer reactions around the region with $R_{\text{Dic}} < r_{\text{min}} \leq R_N$.

(iv) Fusion reactions are confined within the region $0 \leq r_{\text{min}} \leq R_F$.

Here, $R_N$ is the grazing range of nuclear force. $R_{\text{Dic}}$ and $R_F[\approx 1.0(A_1^{1/3} + A_2^{1/3})]$ are the minimum distances for the deep inelastic collision and fusion, respectively.

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. In general, the total cross-section for these reactions may be estimated as,

$$\sigma = \pi R^2 = \pi \lambda^2 \ell^2$$

(3)

The cross-sections for fusion and for deep inelastic scattering may be represented by using the equation (3) as;

$$\sigma_{\text{DIC}} = \pi \lambda^2 (\ell_{\text{DIC}}^2 - \ell_F^2),$$

(4)

$$\sigma_F = \pi \lambda^2 \ell_F^2,$$

(5)

The division of these cross-sections is shown in Fig 1.3. The partial reaction cross-section for such a collision at a given energy $E$ may be given by[3],

\[7\]
\[ \sigma_{t}^{R}(E) = \pi \lambda^{2}(2\ell + 1)T_{\ell}(E) \]  

Where, \( T_{\ell}(E) \) is the transmission coefficient of the \( \ell^{th} \) partial wave for the potential \( V_{\ell}(r) \) at energy \( E \). \( \ell_{F} \) and \( \ell_{DIC} \) are the orbital angular momentum for the HI interactions (fusion and deep inelastic scattering). In the 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,

Fig. 1.3 A TYPICAL REPRESENTATION OF DISTRIBUTION OF TOTAL REACTION CROSS-SECTION INTO THE CROSS-SECTIONS FOR FUSION \( (\sigma_{F}) \), DEEP INELASTIC SCATTERING \( (\sigma_{DIC}) \) AND DIRECT REACTIONS \( (\sigma_{D}) \), AS A FUNCTION OF ANGULAR MOMENTUM. THE HIGHER PARTIAL WAVES CONTRIBUTE MAINLY TO ELASTIC SCATTERING \( (\sigma_{EL}) \) AND COULOMB EXCITATION \( (\sigma_{CE}) \)
\[ V_{\ell}(r) = V_c(r) + V_n(r) + V_{\text{cent}}(r) \] (7)

\[ \sigma_{\ell}^R(E) = \pi \lambda^2 (2\ell + 1) T_{\ell}(E) \] (8)

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

\[ V_c(r) = \frac{1}{4\pi \varepsilon_o} \frac{Z_p Z_T e^2}{r} \] for \( r \geq R_c \) (9)

\[ V_c(r) = \frac{1}{4\pi \varepsilon_o} \frac{Z_p Z_T e^2}{2R_c} (3 - \frac{r^2}{R_c^2}) \] for \( r \leq R_c \) (10)

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

\[ V_n(r) = \frac{V_o}{1 + \exp\left(\frac{r-R}{a}\right)} \] (11)

where,

\[ R = r_o (A_T^{1/3} + A_P^{1/3}) \] (12)

and

\( V_{\text{cent}}(r) \) is the repulsive centrifugal potential given by,

\[ V_{\text{cent}}(r) = \frac{\hbar^2 \ell (\ell + 1)}{2\mu r^2} \] (13)
Here, $Z_p$ and $Z_T$ 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), $\ell$ the angular momentum and $\mu$ the reduced mass of the interacting nuclei. $V_o$ is the depth of the potential, $a$ the diffuseness parameter and $r_o=1.31$ fm. As a representative case, the effective potential $V(\ell)$ for the system $^{16}O + ^{169}Tm$, as a function of separation between interacting ions $(r)$, is shown in Fig. 1.4 for different values of $\ell$.

It may, further, be pointed out that at low energies and larger impact parameters, when the two ions pass through each other at distances larger than the range of the nuclear interaction, they interact only through their Coulomb fields and elastic scattering may take place as only $V_c$ and $V_{cent}$ are important. For grazing impact parameter $b_{gr}$, processes like inelastic scattering and nucleon transfer may take place. This may be due to the overlapping of the tails of nuclear wave functions. On further reduction of impact parameter, the wave functions of the two interacting nuclei overlap considerably and a part of the relative kinetic energy may be converted into internal excitation before the two separates into target and projectile like systems. These deep inelastic collisions take place at energies of the order of few MeV/A above the Coulomb barrier. At still lower values of impact parameter the two ions may come within the range of nuclear interactions and may fuse.

Classically, nuclear interactions can take place if the center of mass energy ($E_{CM}$) of the two ions is high enough to overcome the Coulomb barrier.
Fig. 1.4 PLOTS OF EFFECTIVE POTENTIAL $V_r(r)$ AS A FUNCTION OF RELATIVE SEPARATION ($r$) BETWEEN THE INTERACTING IONS FOR THE SYSTEM $^{16}O + ^{169}Tm$. 
The projectile may fuse with the target nucleus and a number of nuclear reactions may take place. At lower incident energies and for smaller values of impact parameters, the incident projectile may completely fuse with the target nucleus resulting in the formation, first of a composite system which, may undergo thermal equilibration to become a compound nucleus. PE-emission may take place during the equilibration of the composite system. Such kind of process is termed as complete fusion (CF). If only a part of projectile fuses with the target nucleus and the remaining part of it moves on in the beam direction with almost the same velocity as that of incident ion, the process is termed as incomplete fusion (ICF)\[4, 5, 6, 7\]. There are various ways of classifying these processes. One of them is based on the degree of linear momentum transferred from the incident projectile to the composite system. In case of CF, the entire linear momentum of the projectile is transferred to the composite system, while in case of ICF, only a part of projectile fuses with the target nucleus leading to the fractional transfer of linear momentum\[8, 9, 10, 11\]. The fraction of momentum transferred depends on the mass of the fused fragment\[12, 13\].

Though, several methods are available to study the reaction mechanism, however information of considerable value may be extracted from the measurement and analysis of excitation functions (EFs), recoil range distributions and angular distributions of the residues produced in HI interaction. In the HI reactions, the final state has a heavy residual nucleus, light ions and/or \(\gamma\) rays. In most of the experiments the properties like, charge, mass, energy, angular distribution etc., of light particles and/or \(\gamma\) rays emitted in such re-
actions 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 $\gamma$ rays, if radioactive, and by measuring their half lives.

Activation technique is one of the simplest but powerful methods of measuring the excitation functions (EFs) and to deduce important information about the nuclear reaction mechanism. In this technique, the activities induced in the target and catcher assembly are measured off line. The main advantage of the activation technique is the possibility of measuring cross-sections for the production of a large number of residues in a single irradiation thereby reducing beam-time requirements. Activation method is a very important method and is often used for the measurement of the reaction cross-sections. Some of the important advantages of the activation analysis are,

1. **Measurement of the intensity of the induced activity may be done after the stop of irradiation.** Since, measurements are done off-line, no background activities due to incident beam are present.

2. **When a sample is irradiated, several nuclear reactions take place simultaneously.** Many of these reactions leave radioactive nuclides. Each radioactive
nuclide has its own characteristic half life and decay mode. The strength of activities induced in the sample due to these different reactions may be separated out by off-beam analysis of irradiated sample. As such, cross-sections for several reactions may be determined in a single irradiation. This saves considerable accelerator beam time, which is very costly.

3. With the availability of high resolution detectors, it is possible to separate out activities due to different reactions producing $\gamma$-rays of near by energies, accurately. As a result, errors of measurements are quite low and compare well with the similar measurements carried out in the in-beam experiments.

In the HI reactions, at moderate energies a large number of reaction channels are open and the analysis of EFs for these reactions may provide significant information about the CF, ICF and PE emission. The slowly descending tail of the EFs is one of the important signatures of PE 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 $10 \text{MeV/nucleon}$ using activation technique. Crippa et.al.,[4] and Tomar et.al.,[8] have also measured the EFs for CF and ICF in HI 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 limited and no systematic study has been done so far. In order to have a better understanding of these processes, more experimental data covering a wide range of projectile-target pairs over entire periodic ta-
ble and energy is required. In the case of CF entire linear momentum of the projectile is transferred to the target nucleus, the composite system recoils in the beam direction to a larger distance. However, in case of ICF depending on the mass of the fused fragment, relatively low momentum is transferred to the target and the residue recoils at distances that become increasingly smaller with the decreasing mass of the fused projectile fragment. As such, information regarding the relative contribution of CF and ICF in HI reactions may be extracted from the analysis of recoil range measurements of the residues. Some earlier studies[7, 8, 9, 10, 12, 15] 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 5 MeV/nucleon. A significant contribution of ICF to the total reaction cross-section has been observed in these studies.

In this work, as part of a program[13, 15, 16, 17] to study CF, ICF and PE emission in HI induced reactions, activation technique has been used to measure the EFs for several reactions in $^{14}N + ^{128}Te$, $^{16}O + ^{103}Rh$ and $^{16}O + ^{130}Te$ systems at energies near and well above the Coulomb barrier. The experiments have been carried out using the HI beams obtained from the Pelletron accelerator at the Inter University Accelerator Centre (IUAC), New Delhi, India. The measured EFs for various reactions in these systems are compared with the statistical model calculations based on computer codes viz., ALICE-91[19], PACE[20] and CASCADE[21]. Calculations for some reaction cross-sections have also been performed using SUMRULE[22] model. Further, to study the energy dependence and to separate out the relative
contributions of CF and ICF in $^{16}O + ^{169}Tm$ system, the RRDs of several residues have been measured at $\approx 76$ and $81 \ MeV$. An attempt has also been made to measure the angular distribution of residues in the system $^{16}O + ^{169}Tm$ at $\approx 81 \ MeV$. The details of the experiments and measurements are given in Chapters 2 and 3, respectively. Chapter 4 is devoted to the description of computer codes and model. The results and analysis of the measurements are presented in Chapter 5. The references are given at the end of each Chapter.
References


Chapter 2

EXPERIMENTAL TECHNIQUE
The experiments reported in this thesis have been carried out using the 15 UD Pelletron accelerator facility of the Inter University Accelerator Centre (IUAC), New Delhi, India, formerly known as Nuclear Science Centre (NSC). Brief details of Pelletron accelerator are presented in Section 2.1. In the present work activation technique has been used for the measurements of excitation functions (EFs), recoil range distributions (RRDs) and angular distributions of residues. The details of the sample preparation and calibration of detector are described in Sections 2.2 and 2.3, respectively, while the details of irradiation of the targets and the formulations used in calculations are given respectively, in Sections 2.4 and 2.5. A discussion on the detection of residues is given in Section 2.6, while the errors estimated in the measurements are discussed in Section 2.7.

2.1 Pelletron accelerator

A schematic diagram of IUAC Pelletron accelerator is shown in Fig. 2.1.1. The IUAC Pelletron is a 15UD, tandem Van de Graaff electrostatic accelerator. It is capable of accelerating any ion from proton to uranium 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. The high voltage terminal is connected to the tank vertically with ceramic-titanium accelerating tubes. The tank is filled with a high dielectric constant SF$_6$ 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 Cesium Sputtering Ion Source (SNICS) are injected into the accelerator and are accelerated towards the positive terminal.

Fig. 2.1.1 A SCHEMATIC DIAGRAM OF IUAC PELLETRON ACCELERATOR.
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 ion 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 state of the ion after striping depends upon the type of the ion and the terminal voltage. If $q_e$ 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 $q_eV$. Thus, after passing through the two stages of the acceleration, the final energy of the ion in electron volts is given by,

$$E = (q + 1)eV$$

The maximum value of the potential $V$ for IUAC pelletron is 16 MV. The high energy ions are then passed through the analyser magnet which selects the particular ions of the desired energy. The beam of ions is then directed towards the desired experimental area with the help of a seven port switching magnet. A schematic diagram of different beam lines at IUAC Pelletron facility is shown in Fig. 2.1.2.

### 2.2 Sample preparation

The samples used in the present work, were either in the form of self-supporting foils or prepared by vacuum evaporation on thin Al-foils. The self supporting $^{103}$Rh targets were prepared by rolling of thick foils.
The $^{128}\text{Te}$ (enrichment $\approx 87\%$), $^{130}\text{Te}$ (enrichment $\approx 61\%$) and natural $^{169}\text{Tm}$ 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 by an electron beam in an evacuated chamber and is condensed on a suitable substrate. The thickness of each target was determined by the α transmission method which is based on the measurement of the energy lost by α particles while passing through the sample. The 5.485 MeV α-particles from $^{241}Am$ source were used for this purpose. A block diagram of experimental setup used for the thickness measurements is shown in Fig. 2.2.

![Block Diagram for Thickness Measurements](image)

**Fig. 2.2 BLOCK DIAGRAM FOR THE THICKNESS MEASUREMENTS**

The thicknesses of the self-supporting $^{103}Rh$ samples were $\approx 2.0 \text{ mg/cm}^2$, while that of $^{169}Tm$ deposited on Al backing ($\approx 1.1 \text{ mg/cm}^2$) were $\approx 0.5 \text{ mg/cm}^2$. The thicknesses of $^{128}Te$ and $^{130}Te$ deposited on $\approx 6.75 \text{ mg/cm}^2$ Al-foils were $\approx 0.92 \text{ mg/cm}^2$ and $\approx 1.1 \text{ mg/cm}^2$ respectively. The Al backing in case of $^{128}Te$ and $^{130}Te$ samples served as energy degrader as well as catcher foils, so that the recoiling residues may be trapped in catcher thickness. In
case of $^{169}Tm$, the material ($\approx 50 \, mg/cm^2$) was deposited on Al-foils of $\approx 1.1 \, mg/cm^2$. The self-supporting samples of $^{103}Rh$ were cut into size of $1.2 \times 1.2 \, cm^2$ each and were pasted on Al-holders having concentric holes of 1.0 cm diameter. The Al-holders were used for rapid heat dissipation. Al-holders having co-centric holes were also used for other targets to define the geometry.

2.3 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 both for energy as well as efficiency by 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 ($G\varepsilon$) of the detector at a given energy was calculated using the expression,

$$ G\varepsilon = \frac{N_o}{N_{ao}e^{(-\lambda t)\theta}} \quad (15) $$

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 of the
source, $\lambda$ is the decay constant, $t$ is the time lapse between the manufacture of the source and the start of counting and $\theta$ is the branching ratio of the characteristic $\gamma$-ray.

The prominent $\gamma$-rays of the standard $^{152}\text{Eu}$ source used in the present measurements, both for energy calibration of the $\gamma$-ray spectrometer and for the determination of detector efficiency for $\gamma$-rays of different energies, are listed in Table 2.3.

**Table 2.3** The energy and absolute intensities of prominent $\gamma$-rays from standard $\gamma$ source $^{152}\text{Eu}$

<table>
<thead>
<tr>
<th>$\gamma$ 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>867.58</td>
<td>4.21</td>
</tr>
<tr>
<td>964.11</td>
<td>14.50</td>
</tr>
<tr>
<td>1089.71</td>
<td>1.71</td>
</tr>
<tr>
<td>1112.08</td>
<td>13.60</td>
</tr>
<tr>
<td>1212.90</td>
<td>1.20</td>
</tr>
<tr>
<td>1299.16</td>
<td>1.63</td>
</tr>
<tr>
<td>1408.00</td>
<td>20.80</td>
</tr>
</tbody>
</table>
The absolute intensities of these \( \gamma \)-rays are also listed in the table. In the present measurements, the standard \( \gamma \)-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 \( \gamma \)-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,

\[
G\varepsilon = a_0 + a_1X + a_2X^2 + a_3X^3 + a_4X^4 + a_5X^5
\]

(16)

Where, \( X \) being the energy of the characteristic \( \gamma \)-ray and \( a_0, a_1, a_2, a_3, a_4 \) and \( a_5 \) being the coefficients having different values for different source-detector distances. A typical geometry dependent efficiency curve as a function of \( \gamma \) ray energy is shown in Fig. 2.3.

2.4 Irradiation

In the present work, samples were irradiated separately for (a) the measurement of excitation functions (b) the measurement of recoil ranges and (c) the measurement of angular distribution of reaction residues. Irradiations for all the three measurements were performed in the General Purpose Scattering Chamber (GPSC) of 1.5 diameter. This Chamber was selected because of
the in-vacuum sample transfer facility of the chamber. In vacuum transfer of
the irradiated samples considerably reduced the time lost between the stop
of irradiation and the beginning of counting and thus induced activities of
short half lives may be recorded.

![Graph showing a typical geometry dependent efficiency curve as a function of γ-ray energy](image)

**Fig. 2.3** A TYPICAL GEOMETRY DEPENDENT EFFICIENCY CURVE AS A FUNCTION OF γ- RAY ENERGY

### 2.4.1 Measurement of excitation functions

Stacked foil technique has been used for the measurement of EFs. In this
technique a number of foils of the target material are irradiated as a stack.
Different foils of the stack are thus irradiated with the beam of different
energies. In the present experiment, 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. However, in case of $^{128}Te$, six samples were irradiated individually by $^{14}N^{5+}/6+$ beam at energies $\approx 64, 71, 76, 81, 86$ and $90 \text{ MeV}$. The beam currents of $\approx 5 \text{ pA}$ were employed for irradiation and the duration of each irradiation was kept $\approx 3 \text{ h}$, keeping in view the half lives of interest. The samples of $^{103}Rh, ^{130}Te$ and $^{169}Tm$ were irradiated using $^{18}O^{7+}$ beam. In case of $^{103}Rh$, two stacks containing three samples each were irradiated at $\approx 80$ and $85 \text{ MeV}$, respectively. For $^{130}Te$, two stacks of two samples each were prepared and irradiated at $\approx 85$ and $90 \text{ MeV}$, respectively. The beam energy on each sample was calculated using the stopping power tables of Northcliffe and Schilling[1]. In case of first $^{103}Rh$ stack irradiated at $\approx 80 \text{ MeV}$, the incident energies on different foils were $\approx 80, 68$ and $56 \text{ MeV}$. However, in the second stack irradiated at $\approx 85 \text{ MeV}$, the incident energies on different foils were $\approx 85, 73$ and $60 \text{ MeV}$. Similarly, in case of $^{130}Te$ stacks energy range from $\approx 61$ to $90 \text{ MeV}$ was covered. Keeping in view the half lives of interest, irradiations for the samples in $^{103}Rh$ and $^{130}Te$ stacks were carried out for $\approx 4 \text{ h}$. The typical experimental set up used in the present measurements for excitation functions is shown in Fig. 2.4.1.1.

The two silicon surface barrier detectors $D_1$ and $D_2$ (Rutherford monitors) were kept at $30^\circ$ with respect to the direction of the beam at the forward angle, to record the scattered incident ions for flux normalization. The incident flux was also determined from the total charge collected in the Faraday
cup. Flux of incident beam determined from the counts of Rutherford monitors and from the integrated current counts of Faraday cup were found to agree with each other within 5%.

![Diagram of experimental setup](image)

**Fig. 2.4.1.1 TYPICAL EXPERIMENTAL SET UP FOR HEAVY ION IRRADIATION**

The residual nuclei trapped in the samples were counted along with Al-catcher foils. These residues were identified by their characteristic γ-rays and by their measured half lives as well. The observed γ-rays spectrum for $^{16}O + ^{103}Rh$ system at $\approx 85$ MeV is shown in Fig. 2.4.1.2. For clear view, this spectrum is divided into two parts, from channel number 1 to 4000 and than 4000 to 7000, as shown in Figs. 2.4.1.2(a) and (b). Various peaks in the spectrum correspond to different residues produced via different reaction channels.
Fig. 2.4.1.2 THE OBSERVED γ-RAY SPECTRUM OF $^{103}\text{Rh}$ SAMPLE IRRADIATED BY $^{16}\text{O}^+$ BEAM AT ≈85 MeV
2.4.2 Measurement of recoil range distributions of residues.

In the present work, the recoil range distributions (RRDs) for various radioactive residues produced in the interaction of $^{16}O$ beam with $^{169}Tm$ target nucleus have been measured at $\approx76$ and $81 \ MeV$. In the irradiation chamber (GPSC) the target was mounted with Al-backing facing the beam so that the catcher stack immediately followed the $\approx50 \ \mu g/cm^2$ Thulium layer. The beam energies incident on front Al surface were $\approx80$ and $85 \ MeV$, respectively. After an energy loss of $\approx4 \ MeV$ in the Al thickness the incident beam energies were reduced to $\approx76$ and $81 \ MeV$ on the Tm material. A stack of thin Al-catcher foils of the thicknesses varying from $\approx20 - 68 \ \mu g/cm^2$ was used to trap the recoiling nuclei. The irradiation of the targets was performed $\approx10 \ h$ duration with a beam current $\approx10 \ pnA$. A typical arrangement of the target and the catcher assembly for the RRD measurements is shown in Fig. 2.4.2.1. The Al catcher-thicknesses used in the present experiments for the RRD measurements at $\approx76$ and $81 \ MeV$ are given in Table 2.4.2.

![Fig. 2.4.2.1 TYPICAL ARRANGEMENT OF THE TARGET AND THE CATCHER ASSEMBLY USED FOR RECOIL RANGE MEASUREMENTS](image)

33
Table 2.4.2 Catcher thicknesses used for the RRD measurements

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Thickness in $\mu g/cm^2$ for the irradiation at $\approx 76 \text{ MeV}$</th>
<th>Thickness in $\mu g/cm^2$ for the irradiation at $\approx 81 \text{ MeV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.6</td>
<td>56.1</td>
</tr>
<tr>
<td>2</td>
<td>21.6</td>
<td>62.6</td>
</tr>
<tr>
<td>3</td>
<td>24.0</td>
<td>63.9</td>
</tr>
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<td>4</td>
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</tr>
<tr>
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</tr>
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<td>16</td>
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<td>-</td>
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<td>17</td>
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<td>-</td>
</tr>
<tr>
<td>18</td>
<td>32.1</td>
<td>-</td>
</tr>
</tbody>
</table>

Both, the targets and the catchers were prepared by vacuum evaporation
the thicknesses of the samples and the catchers as already mentioned 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[1] 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[6] at IUAC, New Delhi.

A typical \( \gamma \)-ray spectrum of Al-catcher foil at the cumulative catcher thickness \( \approx 378 \text{ mg/cm}^2 \) is shown in Fig. 2.4.2.2. The peaks in the spectrum arise due to various residues produced in the \(^{16}\text{O} + ^{169}\text{Tm}\) system at 81 MeV beam energy. In order to see the various peaks clearly the spectrum is divided into two parts from channel number 1-3000 and 3000-6000, as shown in figs. 2.4.2.2(a) and (b).

The experimentally measured cross-sections \( (\sigma) \) for a particular reaction product in different catcher foils were obtained using equation (19). 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 yields have 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 Chapter 3 and 5 of the thesis.
Fig. 2.4.2.2 A TYPICAL γ-RAY SPECTRUM OF Al-CATCHER FOIL AT CUMULATIVE THICKNESS ≈378 mg/cm². VARIOUS PEAKS CORRESPOND TO THE RESIDUES PRODUCED IN THE SYSTEM $^{16}O + ^{169}Tm$ AT 81 MeV BEAM ENERGY
2.4.3 Measurement of angular distributions of residues.

In the present work, the angular distribution for various radioactive residues produced in the interaction of $^{16}O$ beam with $^{169}Tm$ target nucleus have also been measured at $\approx 81$ MeV. A typical arrangement of the target and catcher assembly used for the angular distribution measurements is shown in Fig. 2.4.3.1. $^{169}Tm$ material ($\approx 47.5 \mu g/cm^2$) deposited on Al foil was used as the sample and was kept normal to the beam direction with Al surface, facing the beam. The beam energy incident on Al surface was $\approx 85$ MeV. After an energy loss of $\approx 4$ MeV in the Al thickness the incident beam energy was reduced to $\approx 81$ MeV on the Tm material. Annular aluminum catchers of thickness $\approx 0.3 \text{ mm}$ with diameters 0.81, 1.29, 1.95, 2.64, 3.27, 5.46 and 6.4 cm respectively, were used to trap the recoiling nuclei emitted at different angles. The arrangement of annular catchers was placed 1.8 cm behind the target for collecting the residue emitted in different angular ranges viz., $0^\circ - 13^\circ$, $13^\circ - 21^\circ$, $21^\circ - 30^\circ$, $30^\circ - 39^\circ$, $39^\circ - 45^\circ$, $45^\circ - 60^\circ$ and $60^\circ - 64^\circ$.

The irradiation was carried out for about 11 h with a beam current of $\approx 7 \text{ pnA}$. The activities induced in each catcher were followed off-line for about two weeks using a precalibrated high resolution (2 keV for 1.33 MeV $\gamma$-ray of $^{60}Co$) HPGe detector of 100 c.c. active volume of CANBERRA coupled to CAMAC based software FREEDOM[6] at IUAC, New Delhi.

The observed gamma ray spectra of Al-catcher rings forming angular range $0^\circ - 13^\circ$, $13^\circ - 21^\circ$ and $21^\circ - 30^\circ$ are shown in Fig. 2.4.3.2. While spectra
covering the angular ranges 30° - 39°, 39° - 45°, 45° - 60° and 60° - 64° are shown in Fig. 2.4.3.3, various peaks in these spectra correspond to different reaction channels. The γ peaks corresponding to alpha emission channel are shown in inset for their clear view in Fig. 2.4.3.4.

Fig. 2.4.3.1 TYPICAL ARRANGEMENT OF THE TARGET AND CATCHER ASSEMBLY USED FOR THE ANGULAR DISTRIBUTION MEASUREMENTS.

The cross-sections (σ) for a particular reaction product in different catcher foils were obtained using equation (19). Measured angular distributions for various residues are presented in Chapter 3 and are discussed in Chapter 5 of the thesis, respectively.
Fig. 2.4.3.2 TYPICAL $\gamma$-RAY SPECTRA OF Al-CATCHER RINGS IN THE ANGULAR RANGES $0^\circ$ – $13^\circ$, $13^\circ$ – $21^\circ$ and $21^\circ$ – $30^\circ$. VARIOUS PEAKS CORRESPOND TO THE RESIDUES POPULATED IN THE $^{16}O + ^{169}Tm$ SYSTEM AT 81 $MeV$
Fig. 2.4.3.3 TYPICAL $\gamma$-RAY SPECTRA OF AI-CATCHER RINGS COVERSING ANGULAR RANGES $30^\circ - 39^\circ$, $39^\circ - 45^\circ$, $45^\circ - 60^\circ$ and $60^\circ - 64^\circ$. VARIOUS PEAKS CORRESPOND TO THE RESIDUES POPULATED IN THE $^{16}O + ^{169}Tm$ SYSTEM AT 81 MeV.
Fig. 2.4.3.4 TYPICAL γ-RAY SPECTRA OF AL-CATCHER RINGS COVERING THE ANGLES 0° - 13°. INSET SHOWS THE 360.7 AND 365.6 keV γ-RAYS CORRESPONDING TO THE RESIDUE $^{181}\text{Re}$ SYSTEM $^{16}\text{O} + ^{169}\text{Tm}$ AT 81 MeV BEAM ENERGY
2.5 Determination of the 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 binary reaction may be represented as,

\[
a + X \rightarrow Y + b
\]  \hspace{1cm} (17)

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

\[
\sigma_r = \frac{\text{Number of events } X(a, b)Y/\text{area}}{N_0 \, \phi \, t}
\]  \hspace{1cm} (18)

Where, \( N_0 \) is the number of the 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 \( \sigma_r(E) \) is given by the expression[2],

\[
\sigma_r(E) = \frac{A \exp(\lambda t_2)}{N_0 \phi \theta K(G\varepsilon)[1 - \exp(-\lambda t_1)][1 - \exp(-\lambda t_3)]}
\]  \hspace{1cm} (19)

Where, \( A \) is the total activity counts recorded during the accumulation time \( t_3 \) of the induced activity of decay constant \( \lambda \), \( N_0 \) the number of the 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 \( G \) the geometry dependent efficiency of the detector. The factor \([1 - \exp(-\lambda t_1)]\) takes care of the decay of residues 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 for the target material.

### 2.6 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 their ground states by emitting characteristic \( \gamma \)-rays. In order to determine the fusion cross sections, two methods may be used. One is IN-BEAM method in which the reaction residues may be identified directly and the other is OFF-BEAM method in which the radioactive residues 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 a measure of the production of that particular evaporation residue. The main advantage of this method is 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 foil by irradiating them with a flux of heavy ion beam. The irradiation may be followed by off line measurement of the activities induced in the target and the catcher assembly. In such measurements, the \( \gamma \)-ray spectrum of each irradiated sample was recorded at increasing times and radioactive residues were identified by their characteristic \( \gamma \) radiations as well as by their half lives. In some case, \( \gamma \)-rays emitted by two different residues were of nearly same energy. The contribution 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 have been measured if the half life of the precursor is consid-
erably 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 the residue and the half lives of the precursor and the residue. In such cases, the decay analysis given by Cavinato et. al.,[3] has been used in order to obtain contributions of the precursor decay.

During the irradiation, if a precursor ′ is formed with cross section ′, and it decays with a half life of ′ and a branching ratio ′, to a daughter nucleus ′ which is produced with the cross section ′ during the irradiation and decays with a half life ′, then decay equations for ′< ′ (′ is the irradiation time) may be given as:

\[
\frac{dN_P}{dt} = -\lambda_P N_P + \sigma_P n\phi
\]  

\[
\frac{dN_D}{dt} = -\lambda_D N_D + \sigma_D n\phi + P_P \lambda_P N_P
\]

Where, \(N_P\) and \(N_D\) are the number of the parent and the daughter nuclei in the sample, respectively. \(\lambda_P\) and \(\lambda_D\) are the decay constants for the parent and daughter nuclei, respectively. \(\phi\) is the flux of incident beam per unit time and \(n\) the number of the target nuclei in the sample. To solve equations (20) and (21), equation (20) is multiplied by the \(P_P \lambda_P/(\lambda_P - \lambda_D)\) and then
added with equation (21), to get the following expression;

\[
\frac{d}{dt} \left( N_D + \frac{P_P \lambda_P}{\lambda_P - \lambda_D} N_P \right) = -\lambda_D \left( N_D + \frac{P_P \lambda_P}{\lambda_P - \lambda_D} N_P \right) + \left( \sigma_D + \frac{P_P \lambda_P}{\lambda_P - \lambda_D} \sigma_P \right) \phi_n
\]  

(22)

Equation (22) becomes,

\[
\frac{dN_{\text{cum}}}{dt} = -\lambda_D N_{\text{cum}} + \sigma_{\text{cum}} n \phi
\]  

(23)

Where, \( N_{\text{cum}} = N_D + \frac{[P_P \lambda_P/(\lambda_P - \lambda_D)] N_P} \) and \( \sigma_{\text{cum}} = \sigma_D + \frac{[P_P \lambda_P/(\lambda_P - \lambda_D)] \sigma_P} \). As, such cumulative cross section \( \sigma_{\text{cum}} \), for the production of the daughter is given by the relation;

\[
\sigma_{\text{cum}} = \sigma_D + P_P \frac{T_{1/2}^D}{T_{1/2}^D - T_{1/2}^B} \sigma_P
\]  

(24)

The branching ratio \( P_P \) has been taken from reference[4].

In case where the precursor \( A \) undergoes two step successive decay of the type \( A \rightarrow B \rightarrow C \), the cumulative cross-section for the production of \( C \) is given by,

\[
\sigma_{\text{cum}} = \sigma_C + P_B \frac{T_{1/2}^C}{T_{1/2}^C - T_{1/2}^B} \sigma_B + P_A P_B \frac{(T_{1/2}^C)^2}{(T_{1/2}^C - T_{1/2}^A)(T_{1/2}^C - T_{1/2}^B)} \sigma_A \sigma_B
\]  

(25)
The above expression has been used for separating the contribution of precursor decay from the measured cumulative cross-section.

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\cite{5} of these calculated values is then taken as the measured cross-section. 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,

\[ \bar{X} = \frac{\sum W_i X_i}{\sum W_i} \]  \hspace{1cm} (26)

Here,

\[ W_i = \frac{1}{\Delta X_i^2} \]  \hspace{1cm} (27)

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

\[ \text{I.E.} = [\sum W_i]^{-1/2} \]  \hspace{1cm} (28)

while the external error (E.E.) is given by,
Equation (28) depends entirely on the errors of individual observations, whereas equation (29) 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.

2.7 Experimental uncertainties

Critical evaluation of uncertainties that are likely to introduce errors in the measured cross-sections reflects the quality of measurements. Following factors may introduce errors in the present measurements.

1. Non-uniform thickness of the target material and inaccurate estimate of foil thickness may lead to the uncertainty in the determination of the number of the target nuclei. This in turn will introduce error in the measured cross-sections. 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 acciden-
tal stop of beam or appreciable fluctuation of the beam intensity was recorded and taken care of while calculating the total irradiation time, average beam current and decay of the induced activities.

3. Dead time of counting is likely to introduce errors in determining the count rates. In the present work, dead time of the counting was kept $\leq 10\%$ by suitably adjusting the sample detector distance. Further, correction for the dead time was applied in the recorded count rate.

4. Uncertainty in the fitting of the efficiency curve ($\leq 3\%$) and also the solid angle effect ($\leq 2\%$)[7] 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 minimised by accumulating the data for a longer time ($\approx 3000$ sec). The statistical fluctuation in efficiency is estimated to be $\leq 2\%$.

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[1].

These errors exclude the uncertainty of the nuclear data like branching ratio, decay constant etc., which have been taken from the Table of Isotopes[8].
References


[6] FREEDOM, Data acquisition and analysis system designed to support the accelerator based experiments at the Inter University Accelerator Centre, New Delhi, India.


With a view to study the complete fusion (CF) and incomplete fusion (ICF) in nuclear reactions induced by \(^{14}\)N and \(^{16}\)O ions, experiments have been performed to measure the excitation functions (EFs), the recoil range distributions (RRDs) and the angular distributions of the residues. The systems studied, the parameter measured, energy range covered in the present measurements and the Coulomb barrier (C.B.) for each of these systems are presented in Table 3.0.

**Table 3.0** List of systems studied, measurements done along with the energy range and Coulomb barrier.

<table>
<thead>
<tr>
<th>Systems studied</th>
<th>Measurements</th>
<th>Energy range</th>
<th>C.B.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{14})N + (^{128})Te → (^{142})Pr</td>
<td>EF</td>
<td>(\approx 64-90) MeV</td>
<td>(\approx 47) MeV</td>
</tr>
<tr>
<td>(^{16})O + (^{103})Rh → (^{119})I</td>
<td>EF</td>
<td>(\approx 56-85) MeV</td>
<td>(\approx 48) MeV</td>
</tr>
<tr>
<td>(^{16})O + (^{130})Te → (^{146})Nd</td>
<td>EF</td>
<td>(\approx 61-90) MeV</td>
<td>(\approx 53) MeV</td>
</tr>
<tr>
<td>(^{16})O + (^{169})Tm → (^{185})Ir</td>
<td>RRD &amp; Angular Dist.</td>
<td>(\approx 76 &amp; 81) MeV</td>
<td>(\approx 66) MeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\approx 81) MeV</td>
</tr>
</tbody>
</table>

Angular Dist. The excitation functions for twenty three reactions viz., \(^{128}\)Te\(^{(14\, N, 4n)}\)\(^{138m}\)Pr, \(^{128}\)Te\(^{(14\, N, 5n)}\)\(^{137}\)Pr, \(^{128}\)Te\(^{(14\, N, p4n)}\)\(^{137}\)Ce, \(^{128}\)Te\(^{(14\, N, \alpha 6n)}\)\(^{132}\)La, \(^{128}\)Te\(^{(14\, N, \alpha 2pm)}\)\(^{135m}\)Cs, \(^{128}\)Te\(^{(14\, N, 2\alpha 2pn)}\)\(^{131}\)I, \(^{128}\)Te\(^{(14\, N, 3\alpha)}\)\(^{130}\)I, \(^{103}\)Rh\(^{(16\, O, pn)}\)\(^{117}\)Te, \(^{103}\)Rh\(^{(16\, O, 2p)}\)\(^{117}\)Sb, \(^{103}\)Rh\(^{(16\, O, 2\alpha)}\)\(^{117}\)In, \(^{103}\)Rh\(^{(16\, O, 2\alpha 2n)}\)\(^{109}\)In, \(^{103}\)Rh\(^{(16\, O, 3\alpha n)}\)\(^{106m}\)Ag, \(^{103}\)Rh\(^{(16\, O, 3\alpha 3n)}\)\(^{104g}\)Ag,
The recoil range and the angular distributions of the residues populated in reactions $^{169}\text{Tm}(^{16}O,3n)^{182}\text{Ir}$, $^{169}\text{Tm}(^{16}O,4n)^{181}\text{Ir}$, $^{169}\text{Tm}(^{16}O,pn)^{183}\text{Os}$, $^{169}\text{Tm}(^{16}O,p2n)^{182}\text{Os}$, $^{169}\text{Tm}(^{16}O,p3n)^{181}\text{Os}$, $^{169}\text{Tm}(^{16}O,\alpha)^{181}\text{Re}$, $^{169}\text{Tm}(^{16}O,2\alpha pn)^{175}\text{Hf}$, $^{169}\text{Tm}(^{16}O,2\alpha p5n)^{171}\text{Hf}$, $^{169}\text{Tm}(^{16}O,3\alpha n)^{172}\text{Lu}$ and $^{169}\text{Tm}(^{16}O,3\alpha 2n)^{171}\text{Lu}$ have been measured in present experiments. The RRDs of residues produced in $^{16}O+^{169}\text{Tm}$ system have been measured at $\approx 76$ and 81 $MeV$ beam energies. With a view to get complementary information about the linear momentum transfer, angular distributions of residues produced in the system $^{16}O+^{169}\text{Tm}$ have also been measured at incident energy $\approx 81$ $MeV$. Further, details of these measurements are given in Section 3.2. To the best of our knowledge the presently measured excitation functions, recoil ranges and angular distributions are being reported for the first time.

### 3.1 The excitation functions

#### 3.1.1 System: $^{14}_7\text{N}+^{128}_5\text{Te}$

Excitation functions for eight reactions[1], listed in the Table 3.1.1(a), have been measured in the energy range $\approx 64$ to 90 $MeV$. The reaction residue, characteristic $\gamma$-ray identifying the residue, and their branching ratios are also provided in Table 3.1.1(a).
Table 3.1.1(a) Reactions, residues, identified γ-rays and their branching ratios.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Reaction</th>
<th>Residue</th>
<th>$E_\gamma$(keV)</th>
<th>Branching ratio(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$^{128}Te(^{14}N,4n)$</td>
<td>$^{138m}Pr$</td>
<td>302.7, 390.9</td>
<td>80.0, 6.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>547.5, 788.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1037.8</td>
</tr>
<tr>
<td>2.</td>
<td>$^{128}Te(^{14}N,5n)$</td>
<td>$^{137}Pr$</td>
<td>434.3, 837.1</td>
<td>1.3, 1.1</td>
</tr>
<tr>
<td>3.</td>
<td>$^{128}Te(^{14}N,4n)$</td>
<td>$^{137g}Ce$</td>
<td>447.2</td>
<td>2.2</td>
</tr>
<tr>
<td>4.</td>
<td>$^{128}Te(^{14}N,α5n)$</td>
<td>$^{133}La$</td>
<td>302.4</td>
<td>1.2</td>
</tr>
<tr>
<td>5.</td>
<td>$^{128}Te(^{14}N,α6n)$</td>
<td>$^{129g}La$</td>
<td>540.4</td>
<td>7.8</td>
</tr>
<tr>
<td>6.</td>
<td>$^{128}Te(^{14}N,α2pn)$</td>
<td>$^{135m}Cs$</td>
<td>786.9, 840.0</td>
<td>99.7, 96.0</td>
</tr>
<tr>
<td>7.</td>
<td>$^{128}Te(^{14}N,2α2pn)$</td>
<td>$^{131}I$</td>
<td>284.3, 364.4</td>
<td>6.1, 81.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>637.0</td>
</tr>
<tr>
<td>8.</td>
<td>$^{128}Te(^{14}N,3α)$</td>
<td>$^{130g}I$</td>
<td>536.1, 668.6</td>
<td>99.0, 96.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>739.5</td>
</tr>
</tbody>
</table>

Reaction residues have been identified by their characteristic γ-rays and half lives. In some cases more than one γ-ray of the residues have been identified. Cross-section has been calculated separately from the intensity of each of the observed γ-ray. Each reaction has been discussed in details in the following:

1. $^{128}Te(^{14}N,4n)$ channel [$residue=^{138m}Pr$, $T_{1/2} = 2.1$ h, $J^\pi = 7^-$]

The evaporation residue $^{138}Pr$ may be formed by the complete fusion of $^{14}N$ with $^{128}Te$ forming the composite system $^{142}Pr$, followed by the evaporation
of 4 neutrons. The residual nucleus $^{138}Pr$ has two states, the ground state $^{138g}Pr$ and the metastable state $^{138m}Pr$. In the present experiments only the state $^{138m}Pr$ has been observed. The metastable state was identified by the characteristic $\gamma$-rays of energies 302.7, 390.9, 547.5, 788.7 and 1037.8 keV, and was confirmed from their measured half life of 2.1 $h$. The residue $^{138g}Pr$ has a half life of only 1.45 $m$ and as such only the metastable state $^{138m}Pr$ could be recorded.

2. $^{128}Te(^{14}N,5n)$ channel [residue=$^{137}_{58}Pr$, $T_{1/2} = 1.28$ h, $J^\pi = 5/2^+$]

The evaporation residue $^{137}Pr$ may be populated by the complete fusion of $^{14}N$ with $^{128}Te$ followed by the evaporation of 5 neutrons from the compound nucleus $^{142}Pr$.

3. $^{128}Te(^{14}N,p4n)$ channel [residue=$^{137}_{58}Ce$, $T_{1/2} = 9.0$ h, $J^\pi = 3/2^+$]

The evaporation residue $^{137}_{58}Ce$ is likely to be formed by the complete fusion of $^{14}N$ with $^{128}Te$ followed by the evaporation of a proton and 4 neutrons from the compound nucleus $^{142}Pr$. The residue $^{137}_{58}Ce$ may also be populated by the $\beta^+$ and/or EC decay of higher charge precursor isobar $^{137}_{59}Pr$ produced via $^{128}Te(^{14}N,5n)$ channel. As such, the measured activity of $^{137}_{58}Ce$ may have contribution from precursor decay also.

The presently measured cross-sections for the production of various residues in the complete fusion of $^{14}N$ with $^{128}Te$ are tabulated in Table 3.1.1(b).
Table 3.1.1(b) Cross-sections for the residues $^{138m}Pr$, $^{137}Pr$ and $^{137g}Ce$.

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma^{(138m)Pr}$ (mb)</th>
<th>$\sigma^{(137)Pr}$ (mb)</th>
<th>$\sigma^{(137g)Ce}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>64.0±0.8</td>
<td>225±55</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>71.1±0.8</td>
<td>381±42</td>
<td>456±65</td>
<td>144±19</td>
</tr>
<tr>
<td>75.9±0.7</td>
<td>178±20</td>
<td>463±60</td>
<td>194±21</td>
</tr>
<tr>
<td>81.2±0.6</td>
<td>62±8</td>
<td>577±62</td>
<td>220±35</td>
</tr>
<tr>
<td>85.6±0.5</td>
<td>66±7</td>
<td>611±72</td>
<td>263±50</td>
</tr>
<tr>
<td>89.7±0.5</td>
<td>48±5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

4. $^{128}\text{Te}(^{14N,\alpha5n})$ channel [$residue=^{133}_{57}\text{La}$, $T_{1/2} = 3.9$ h, $J^\pi = 5/2^-$]

The residue $^{133}_{57}\text{La}$ may be produced by the complete fusion of $^{14N}$ with $^{128}\text{Te}$ followed by the evaporation of an $\alpha$ particle and 5 neutrons from the composite system $^{142}\text{Pr}$. The same residual nucleus may also be produced assuming that the $^{14N}$ breaks up into $^{10B}$ and $^{4}\text{He}$ fragments in the presence of field of the target nucleus and the fragment $^{10B}$ fuses with $^{128}\text{Te}$ forming $^{133}_{57}\text{La}$, from which 5 neutrons are emitted. The measured cross sections may, therefore, include contributions from both the complete and incomplete fusion processes.

5. $^{128}\text{Te}(^{14N,\alpha6n})$ channel [$residue=^{132}_{57}\text{La}$, $T_{1/2} = 4.8$ h, $J^\pi = 2^-$]

The residue $^{132}_{57}\text{La}$ may be produced by the complete fusion of $^{14N}$ with $^{128}\text{Te}$ followed by the evaporation of an $\alpha$ particle and 6 neutrons from the
composite system $^{142}Pr$. The same residual nucleus may also be produced if the fragment $^{10}B$ of $^{14}N$ fuses with $^{128}Te$ and six neutrons are emitted. The measured cross sections, therefore, include contributions from both the complete and incomplete fusion processes.

6. $^{128}Te(14N, \alpha2pn)$ channel [$residue=^{135m}Cs, T_{1/2} = 53 m, J^\pi = 19/2^-$]

The residue $^{135m}Cs$ may be produced by the complete fusion of $^{14}N$ with $^{128}Te$ followed by the evaporation of an $\alpha$ particle, 2 protons and a neutron from the composite system $^{142}Pr$. The same residual nucleus may also be produced if the fragment $^{10}B$ of $^{14}N$ fuses with $^{128}Te$ nucleus and two protons & a neutron are emitted. In this case also the measured cross sections, may include contributions from both the CF and ICF processes.

Experimentally measured production cross-sections for $^{133}La$, $^{132}La$ and $^{135m}Cs$ residues by the complete fusion of $^{14}N$ with $^{128}Te$ and the incomplete fusion of $^{14}N$ (fusion of $^{10}B$, if $^{14}N$ undergoes breakup into $\alpha$-particle and $^{10}B$) with $^{128}Te$ are given in Table 3.1.1(c).

7. $^{128}Te(14N, 2\alpha2pn)$ channel [$residue=^{131}I, T_{1/2} = 8.0 d, J^\pi = 7/2^+$]

The residue $^{131}I$ may be produced by the complete fusion of $^{14}N$ with $^{128}Te$ forming $^{142}Pr$ followed by the evaporation of 2$\alpha$ particles, 2 protons and a neutron. The same residual nucleus $^{131}I$ may also be produced if the fragment $^4He$ of $^{14}N$(if $^{14}N$ breaks up into $\alpha$-particle and $^{10}B$) fuses with $^{128}Te$ and a proton is emitted. The measured cross sections for the residue $^{131}I$, therefore, include contributions from both the CF and ICF processes.
Table 3.1.1(c) Cross-sections for the residues $^{133}\text{La}$, $^{132}\text{La}$, $^{135}\text{Cs}$, $^{131}\text{I}$ and $^{130}\text{I}$.  

<table>
<thead>
<tr>
<th>Lab Energy ($\text{MeV}$)</th>
<th>$\sigma^{(133}\text{La)}$ (mb)</th>
<th>$\sigma^{(132}\text{La)}$ (mb)</th>
<th>$\sigma^{(135}\text{Cs)}$ (mb)</th>
<th>$\sigma^{(131}\text{I)}$ (mb)</th>
<th>$\sigma^{(130}\text{I)}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.9±0.7</td>
<td>-</td>
<td>-</td>
<td>46±4</td>
<td>-</td>
<td>2.1±0.5</td>
</tr>
<tr>
<td>81.2±0.6</td>
<td>-</td>
<td>-</td>
<td>6.1±0.6</td>
<td>-</td>
<td>28±4</td>
</tr>
<tr>
<td>85.6±0.5</td>
<td>376±38</td>
<td>18±2</td>
<td>1.2±0.1</td>
<td>98±32</td>
<td>12±2</td>
</tr>
<tr>
<td>89.7±0.5</td>
<td>1435±144</td>
<td>478±48</td>
<td>141±40</td>
<td>36±4</td>
<td>2.0±0.3</td>
</tr>
</tbody>
</table>

8. $^{128}\text{Te}^{(14}\text{N}, 3\alpha)$ channel \[\text{residue}=^{130}\text{I}, \ T_{1/2}=12.36 \text{ h}, \ J^\pi = 5^+\]

The residue $^{130}\text{I}$ may be produced by the complete fusion of $^{14}\text{N}$ with $^{128}\text{Te}$ followed by the evaporation of 3$\alpha$ particles. The same residue $^{130}\text{I}$ may also be produced if the fragment $^4\text{He}$ of $^{14}\text{N}$ fuses with $^{128}\text{Te}$ and one proton & a neutron are emitted. The measured cross sections, therefore, include contributions from both the CF and ICF processes.

Presently, measured production cross-sections for $^{131}\text{I}$ and $^{130}\text{I}$ by the complete and the incomplete fusion of $^{14}\text{N}$ with $^{128}\text{Te}$ are also given in Table 3.1.1(c)

3.1.2 System: $^{16}\text{O} + ^{45}\text{Rh}$

Excitation functions for the reactions listed in Table 3.1.2(a) have been measured in the energy range $\approx$56-85 MeV.
### Table 3.1.2(a) Reactions, residues, identified γ-rays and their branching ratios.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Reaction</th>
<th>Residue</th>
<th>$E_\gamma$(keV)</th>
<th>Branching ratio(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$^{103}$Rh($^{16}$O, $pn$)</td>
<td>$^{117m}$Te</td>
<td>719.7, 886.6</td>
<td>64.7, 1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>923.8, 996.6</td>
<td>6.2, 3.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1090.7</td>
<td>6.9</td>
</tr>
<tr>
<td>2.</td>
<td>$^{103}$Rh($^{16}$O, $p2n$)</td>
<td>$^{116}$Te</td>
<td>628.7</td>
<td>1.0</td>
</tr>
<tr>
<td>3.</td>
<td>$^{103}$Rh($^{16}$O, $2p$)</td>
<td>$^{117}$Sb</td>
<td>158.6</td>
<td>85.9</td>
</tr>
<tr>
<td>4.</td>
<td>$^{103}$Rh($^{16}$O, $2pn$)</td>
<td>$^{116g}$Sb</td>
<td>931.8, 1293.5</td>
<td>24.8, 85</td>
</tr>
<tr>
<td>5.</td>
<td>$^{103}$Rh($^{16}$O, $2pn$)</td>
<td>$^{116m}$Sb</td>
<td>135.5, 407.3</td>
<td>29, 42</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>436.6, 542.8</td>
<td>4.1, 52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>844.0, 972.5</td>
<td>12, 72</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1072.4, 1293.5</td>
<td>21.8, 100</td>
</tr>
<tr>
<td>6.</td>
<td>$^{103}$Rh($^{16}$O, $\alpha$)</td>
<td>$^{115}$Sb</td>
<td>497.4, 489.1</td>
<td>98, 1.3</td>
</tr>
<tr>
<td>7.</td>
<td>$^{103}$Rh($^{16}$O, $2\alpha$)</td>
<td>$^{111g}$In</td>
<td>171.3, 245.4</td>
<td>90.2, 94.0</td>
</tr>
<tr>
<td>8.</td>
<td>$^{103}$Rh($^{16}$O, $2\alpha2n$)</td>
<td>$^{109g}$In</td>
<td>203.2, 623.6</td>
<td>73.5, 6.0</td>
</tr>
<tr>
<td>9.</td>
<td>$^{103}$Rh($^{16}$O, $3\alpha$)</td>
<td>$^{106m}$Ag</td>
<td>451.0, 717.4</td>
<td>27.6, 29.0</td>
</tr>
<tr>
<td>10.</td>
<td>$^{103}$Rh($^{16}$O, $3\alpha3n$)</td>
<td>$^{104g}$Ag</td>
<td>767.8, 555.8</td>
<td>65.9, 92.8</td>
</tr>
</tbody>
</table>

Details of each reaction are discussed in the following:

1. **$^{103}$Rh($^{16}$O, $pn$) channel** [$residue=^{117m}$Te, $T_{1/2} = 62$ m, $J^+ = 1/2^+$]

The evaporation residue $^{117m}$Te is likely to be formed by the complete fusion of $^{16}$O with $^{103}$Rh forming the composite system $^{119}$I followed by the
evaporation of a proton and a neutron from the composite system. The residue $^{117}_{52}Te$ may also be populated by the $\beta^+$ and/or EC decay of higher charge precursor isobar $^{117}_{53}I$. The contribution due to the decay of precursor isobar $^{117}_{53}I$ to the residue $^{117}_{52}Te$ has been separated by using formulations given by the Cavinato et.al., [3].

\[
\sigma^{(117 Te)}_{\text{cum}} = \sigma^{(117g Te)}_{\text{ind}} + 1.03 \times \sigma^{(117g I)}_{\text{ind}}
\]  

(30)

Where, subscript $\text{cum}$ and $\text{ind}$ stand, respectively for cumulative and independent yields. The experimentally determined independent cross-sections for the formation of $^{117}Te$ are given in Table 3.1.2(b).

2. $^{103}Rh^{(16}O, p2n)$ channel [residue=$^{116}_{52}Te$, $T_{1/2} = 2.49$ h, $J^e = 0^+$]

The evaporation residue $^{116}Te$ may be formed by the complete fusion of $^{16}O$ with $^{103}Rh$ forming the composite system $^{119}I$, which may evaporate a proton and two neutrons. The same residue $^{116}_{52}Te$ may also be populated by the $\beta^+$ and/or EC decay of higher charge precursor isobar $^{116}_{53}I$. The contribution due to the decay of precursor isobar $^{116}_{53}I$ to the residue $^{116}_{52}Te$ has also been separated using standard decay formulation[3]. The independent cross-sections deduced from the cumulative yield using equation (31) are given in Table 3.1.2(b).

\[
\sigma^{(116 Te)}_{\text{cum}} = \sigma^{(116 Te)}_{\text{ind}} + 0.97 \times \sigma^{(116 I)}_{\text{ind}}
\]  

(31)
Table 3.1.2(b) Cross-sections for the residues \(^{117}\)Te and \(^{116}\)Te.

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>(\sigma_{\text{cum}}(^{117})Te) (mb)</th>
<th>(\sigma_{\text{ind}}(^{117})Te) (mb)</th>
<th>(\sigma_{\text{cum}}(^{116})Te) (mb)</th>
<th>(\sigma_{\text{ind}}(^{116})Te) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.9±2.6</td>
<td>6.4±0.1</td>
<td>3.0±0.3</td>
<td>52±4</td>
<td>45±4</td>
</tr>
<tr>
<td>60.3±2.5</td>
<td>14.4±0.1</td>
<td>5.9±0.6</td>
<td>182±18</td>
<td>149±18</td>
</tr>
<tr>
<td>68.3±2.3</td>
<td>5.6±0.3</td>
<td>2.4±0.2</td>
<td>228±40</td>
<td>164±40</td>
</tr>
<tr>
<td>72.8±2.2</td>
<td>3.5±0.4</td>
<td>1.1±0.1</td>
<td>210±30</td>
<td>158±30</td>
</tr>
<tr>
<td>78.4±1.6</td>
<td>0.81±0.05</td>
<td></td>
<td>199±25</td>
<td>178±25</td>
</tr>
<tr>
<td>85.5±1.5</td>
<td>0.22±0.04</td>
<td></td>
<td>173±19</td>
<td>169±19</td>
</tr>
</tbody>
</table>

3. \(^{103}\)Rh\(^{(16}\)O,2p) channel \([\text{residue}=^{117}\)Sb, \(T_{1/2} = 2.80\) h, \(J^* = 5/2^+\)]

The evaporation residue \(^{117}\)Sb may be populated by the complete fusion of \(^{16}\)O with \(^{103}\)Rh forming the composite system \(^{119}\)I followed by the evaporation of two protons from the composite system \(^{119}\)I. The residue \(^{117}\)Sb may also be populated by the \(\beta^+\) and/or EC decay of higher charge precursor isobar \(^{117}\)Te. Contribution of precursor decay has been separated\(^3\) and the cumulative as well as the deduced independent yields are given in Table 3.1.2(c).

4. \(^{103}\)Rh\(^{(16}\)O,2pn) channel \([\text{residue}=^{116}\)Sb, \(T_{1/2} = 15.8\) m, \(J^* = 3^+\)]

\([\text{residue}=^{116m}\)Sb, \(T_{1/2} = 60.3\) m, \(J^* = 8^+\)]

In case of reaction \(^{103}\)Rh\(^{(16}\)O,2pn), two states of residue \(^{116}\)Sb \((T_{1/2} = 15.8\) m) and \(^{116m}\)Sb \((T_{1/2} = 60.3\) m) are populated. The two states de-
cay independently by their characteristic γ-rays of energies 931.8 and 135.3 keV. The cross-sections for the two states have been obtained from observed intensities of characteristic γ-rays while the decay of two states has been confirmed by their characteristic half lives. The evaporation residue $^{116}\text{Sb}$ may be formed by the complete fusion of $^{16}\text{O}$ with $^{103}\text{Rh}$ forming the composite system $^{119}I$ followed by the evaporation of two protons and a neutron from it. The residue $^{116}\text{Sb}$ may also be populated via β⁺/EC decay of higher charge precursor isobar of $^{116}\text{Te}$. The contribution of precursor decay has been separated using the formulation given in reference[4]

The presently measured cross-sections for the production of $^{117,166}\text{Sb}$ residues in the complete fusion of $^{16}\text{O}$ with $^{103}\text{Rh}$ system are tabulated in Table 3.1.2(c).

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma_{\text{sum}}(^{117}\text{Sb})$ (mb)</th>
<th>$\sigma_{\text{ind}}(^{117}\text{Sb})$ (mb)</th>
<th>$\sigma_{\text{sum}}(^{116}\text{Sb})$ (mb)</th>
<th>$\sigma(^{116m}\text{Sb})$ (mb)</th>
<th>$\sigma_{\text{ind}}(^{116}\text{Sb})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.9±2.6</td>
<td>15±2</td>
<td>1.4±1.3</td>
<td>54±2</td>
<td>0.4±0.5</td>
<td>42±6</td>
</tr>
<tr>
<td>60.3±2.5</td>
<td>26±6</td>
<td>3.3±1.2</td>
<td>127±7</td>
<td>2±0.3</td>
<td>98±25</td>
</tr>
<tr>
<td>68.3±2.3</td>
<td>27±4</td>
<td>2.7±1.8</td>
<td>106±18</td>
<td>5±0.5</td>
<td>94±41</td>
</tr>
<tr>
<td>72.8±2.2</td>
<td>9±1</td>
<td>0.4±0.2</td>
<td>197±14</td>
<td>6±0.7</td>
<td>102±44</td>
</tr>
<tr>
<td>78.4±1.6</td>
<td>4±0.4</td>
<td>-</td>
<td>106±12</td>
<td>5±0.8</td>
<td>98±37</td>
</tr>
<tr>
<td>85.5±1.5</td>
<td>2.1±0.2</td>
<td>-</td>
<td>166±57</td>
<td>4±0.5</td>
<td>114±76</td>
</tr>
</tbody>
</table>

5. $^{103}\text{Rh}^{(16}\text{O,α)}$ channel \([\text{residue=115}\text{Sb, } T_{1/2} = 32.10 \text{ m, } J^\pi = 5/2^+ ]\)
The evaporation residue $^{115}\text{Sb}$ may be formed by the complete fusion of $^{16}\text{O}$ with $^{103}\text{Rh}$ forming the composite system $^{119}\text{I}$ followed by the evaporation of an $\alpha$ particle. The same residue may also be produced if the fragment $^{12}\text{C}$ of $^{16}\text{O}$ (if $^{16}\text{O}$ undergoes breakup into $\alpha$-particle and $^{12}\text{C}$ fragments) fuses with $^{103}\text{Rh}$ nucleus. As such, the measured cross section for $^{115}\text{Sb}$ include contributions from both the complete as well as incomplete fusion processes.

6. $^{103}\text{Rh}(^{16}\text{O},2\alpha)$ channel [residue=$^{111}\text{In}$, $T_{1/2}=2.8$ d, $J^\pi=9/2^+$]

The residue $^{111}\text{In}$ has been identified by the characteristic $\gamma$-rays of 171.3 and 245.4 keV energies. The evaporation residue $^{111}\text{In}$ is likely to be formed by the complete fusion of $^{16}\text{O}$ with $^{103}\text{Rh}$ forming the composite system $^{119}\text{I}$ which may evaporate two alpha particles. The same residue $^{111}\text{In}$ may also be produced if the fragment $^{8}\text{Be}$ of $^{16}\text{O}$ (if $^{16}\text{O}$ undergoes breakup into two $^{8}\text{Be}$ fragments) fuses with $^{103}\text{Rh}$ nucleus. The measured cross section, may therefore, include contributions from both the complete as well as incomplete fusion processes.

7. $^{103}\text{Rh}(^{16}\text{O},2\alpha2n)$ channel [residue=$^{109}\text{In}$, $T_{1/2}=4.2$ h, $J^\pi=9/2^+$]

The evaporation residue $^{109}\text{In}$ which was identified by 203.2 and 623.6 keV gamma rays and 4.2 h half life may be formed by the complete fusion of $^{16}\text{O}$ with $^{103}\text{Rh}$, followed by the evaporation of two alpha particles and two neutrons from the composite nucleus $^{119}\text{I}$. The same residue may also be produced if the fragment $^{8}\text{Be}$ of $^{16}\text{O}$ (if $^{16}\text{O}$ undergoes breakup into two $^{8}\text{Be}$
fragments) fuses with $^{103}Rh$ followed by the evaporation of two neutrons. The measured cross section thus includes contributions from both the complete as well as incomplete fusion processes.

8. $^{103}Rh(^{16}O, 3\alpha 3n)$ channel [residue=$^{106m}Ag$, $T_{1/2} = 8.28$ d, $J^\pi = 6^+$]

The evaporation residue $^{106m}Ag$ may be formed by the complete fusion of $^{16}O$ with $^{103}Rh$ forming the composite system $^{119}I$ followed by the evaporation of three alpha particles and a neutron from the composite system $^{119}I$. The same residue may also be produced if the fragment $^4He$ of $^{16}O$ (if $^{16}O$ undergoes breakup into $\alpha$ and $^{12}C$ particles) fuses with $^{103}Rh$ nucleus followed by the evaporation of a neutron. The measured cross sections, therefore, include contributions from both the complete as well as incomplete fusion processes.

9. $^{103}Rh(^{16}O, 3\alpha 3n)$ channel [residue=$^{104g}Ag$, $T_{1/2} = 1.15$ h, $J^\pi = 5^+$]

The evaporation residue $^{104g}Ag$ identified by 767.8 and 555.8 keV gammas and 1.1 h half-life, may be formed by the complete fusion of $^{16}O$ with $^{103}Rh$ forming the composite system $^{119}I$ followed by the evaporation of three alpha particles and three neutrons from the compound nucleus $^{119}I$. The same residue may also be produced if the fragment $^4He$ of $^{16}O$ (if $^{16}O$ undergoes breakup into $\alpha$ and $^{12}C$-particles) fuses with $^{103}Rh$ followed by the evaporation of three neutrons. The measured cross sections may therefore, include contributions from both the complete as well as incomplete fusion processes. Experimentally measured cross-sections for the production of $^{115}Sb$, $^{119}In$, $^{105g}In$, $^{106m}Ag$ and $^{104g}Ag$ isotopes at different energies are given in Table 3.1.2(f).
Table 3.1.2(f) Cross-sections for the production of residues $^{115}\text{Sb}$, $^{119}\text{In}$, $^{109}\text{In}$, $^{106}\text{Ag}$ & $^{104}\text{Ag}$.

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma(^{115}\text{Sb})$ (mb)</th>
<th>$\sigma(^{119}\text{In})$ (mb)</th>
<th>$\sigma(^{109}\text{In})$ (mb)</th>
<th>$\sigma(^{106}\text{Ag})$ (mb)</th>
<th>$\sigma(^{104}\text{Ag})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.3±2.5</td>
<td>2.4±0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>68.3±2.3</td>
<td>53±6</td>
<td>0.5±0.1</td>
<td>0.5±0.1</td>
<td>9.0±1.2</td>
<td>-</td>
</tr>
<tr>
<td>72.8±2.2</td>
<td>149±18</td>
<td>3.3±0.3</td>
<td>2.1±0.1</td>
<td>13.4±2.1</td>
<td>-</td>
</tr>
<tr>
<td>78.4±1.6</td>
<td>266±37</td>
<td>4.2±0.6</td>
<td>10.3±0.7</td>
<td>19.4±1.9</td>
<td>2.8±0.3</td>
</tr>
<tr>
<td>85.5±1.5</td>
<td>380±49</td>
<td>18±2</td>
<td>20±2</td>
<td>29±4</td>
<td>5.1±0.5</td>
</tr>
</tbody>
</table>

3.1.3 System: $^{16}\text{O} + ^{130}\text{Te}$

Excitation functions for the reactions listed in the Table 3.1.3(a) have been measured in the energy range $\approx 61$-90 MeV.

Table 3.1.3(a) Reaction, residue, energy of the identified $\gamma$-ray and the branching ratio.

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Reaction</th>
<th>Residue</th>
<th>$E_\gamma$(keV)</th>
<th>Branching ratio(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>$^{130}\text{Te}(^{16}\text{O},5n)$</td>
<td>$^{141}\text{Nd}$</td>
<td>1127</td>
<td>0.8</td>
</tr>
<tr>
<td>2.</td>
<td>$^{130}\text{Te}(^{16}\text{O},3\alpha n)$</td>
<td>$^{139}\text{Ce}$</td>
<td>165.8</td>
<td>80</td>
</tr>
<tr>
<td>3.</td>
<td>$^{130}\text{Te}(^{16}\text{O},3\alpha n)$</td>
<td>$^{133}\text{Xe}$</td>
<td>80.9</td>
<td>73</td>
</tr>
<tr>
<td>4.</td>
<td>$^{130}\text{Te}(^{16}\text{O},3\alpha n)$</td>
<td>$^{133m}\text{Xe}$</td>
<td>233.2</td>
<td>10.3</td>
</tr>
<tr>
<td>5.</td>
<td>$^{130}\text{Te}(^{16}\text{O},3\alpha n)$</td>
<td>$^{131m}\text{Xe}$</td>
<td>163.9</td>
<td>1.97</td>
</tr>
</tbody>
</table>

Details for each reaction are discussed in the following.
1. $^{130}\text{Te}(^{16}\text{O}, 5\text{n})$ channel $[\text{residue}=^{141}\text{Nd}, T_{1/2} = 2.49 \text{ h, } J^\pi = 3/2^+]$

The evaporation residue $^{141}\text{Nd}$ may be formed by the complete fusion of $^{16}\text{O}$ with $^{130}\text{Te}$ followed by the evaporation of five neutrons from the composite system $^{146}\text{Nd}$. The residue $^{141}\text{Nd}$ has been identified by the characteristic $\gamma$-ray of energy 1127 keV and also by its half-life.

2. $^{130}\text{Te}(^{16}\text{O}, 3\alpha\text{n})$ channel $[\text{residue}=^{139}\text{Ce}, T_{1/2} = 137.6 \text{ d, } J^\pi = 3/2^+]$

The evaporation residue $^{139}\text{Ce}$ may be formed by the complete fusion of $^{16}\text{O}$ with $^{130}\text{Te}$, forming the composite system $^{146}\text{Nd}$ which may decay by the evaporation of an alpha particle and three neutrons. The same residue may also be produced if the fragment $^{12}\text{C}$ of $^{16}\text{O}$ (if $^{16}\text{O}$ undergoes breakup into $\alpha$ and $^{12}\text{C}$ fragments) fuses with $^{130}\text{Te}$ followed by the evaporation of three neutrons. The measured cross section includes contributions from both the complete as well as incomplete fusion processes.

3. $^{130}\text{Te}(^{16}\text{O}, 3\alpha\text{n})$ channel $[\text{residue}=^{133}\text{Xe}, T_{1/2} = 5.2 \text{ d, } J^\pi = 3/2^+]$

$[\text{residue}=^{133m}\text{Xe}, T_{1/2} = 2.19 \text{ d, } J^\pi = 11/2^-]$

The evaporation residue $^{133}\text{Xe}$ may be formed by the complete fusion of $^{16}\text{O}$ with $^{130}\text{Te}$ forming the composite system $^{146}\text{Nd}$ followed by the evaporation of three alpha particles and a neutron from it. The same residue may also be produced if the fragment $^4\text{He}$ of $^{16}\text{O}$ (if $^{16}\text{O}$ undergoes breakup into $\alpha$ and $^{12}\text{C}$ particles) fuses with $^{130}\text{Te}$ followed by the evaporation a neutron. The measured cross sections include contributions from both the
complete as well as incomplete fusion processes.

4. $^{130}\text{Te}(^{16}\text{O},3\alpha3n)$ channel [residue=$^{131m}\text{Xe}$, $T_{1/2} = 11.9\text{d}, J^\pi = 11/2^-$]

The evaporation residue $^{131m}\text{Xe}$ is likely to be formed by the complete fusion of $^{16}\text{O}$ with $^{130}\text{Te}$ followed by the evaporation of three alpha particles and three neutrons. The same residue may also be produced if the fragment $^4\text{He}$ of $^{16}\text{O}$(if $^{16}\text{O}$ undergoes break up into $\alpha$ and $^{12}\text{C}$ fragments) fuses with $^{130}\text{Te}$ followed by the evaporation of three neutrons. The measured cross sections include contributions from both the complete as well as incomplete fusion processes. Experimentally measured cross-sections for the reactions in $^{16}\text{O} + ^{130}\text{Te}$ system are given in Table 3.1.3(b).

### Table 3.1.3(b) Cross-sections of for the residues $^{141}\text{Nd}$, $^{139}\text{Ce}$, $^{133m}\text{Xe}$, $^{133}\text{Xe}$ and $^{131m}\text{Xe}$

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma(^{141}\text{Nd})$ (mb)</th>
<th>$\sigma(^{139}\text{Ce})$ (mb)</th>
<th>$\sigma(^{133m}\text{Xe})$ (mb)</th>
<th>$\sigma(^{133}\text{Xe})$ (mb)</th>
<th>$\sigma(^{131m}\text{Xe})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>61.3±2.2</td>
<td>2.2±0.2</td>
<td>-</td>
<td>8±2</td>
<td>5.1±0.8</td>
<td>8±1</td>
</tr>
<tr>
<td>67.1±2.1</td>
<td>20±2</td>
<td>107±11</td>
<td>183±30</td>
<td>30±3</td>
<td>12±2</td>
</tr>
<tr>
<td>83.2±1.8</td>
<td>682±84</td>
<td>890±84</td>
<td>180±25</td>
<td>34±3</td>
<td>180±20</td>
</tr>
<tr>
<td>90.1±1.9</td>
<td>885±110</td>
<td>183±18</td>
<td>477±60</td>
<td>8±1</td>
<td>32±4</td>
</tr>
</tbody>
</table>

3.2 The $^{16}\text{O} + ^{169}\text{Tm}$ SYSTEM: Measurement of recoil range and angular distributions

The recoil ranges and the angular distributions of the residues $^{182}\text{Ir}$, $^{181}\text{Ir}$,
183Os, 182Os, 181Os, 181Re, 175Hf, 171Hf, 172gLu and 171gLu have also been measured. Details of reactions, residues, identified γ-rays and their branching ratios are listed in Table 3.2. For these reactions measurement of excitation functions has already been reported separately[5]. In this section details of the measurement of recoil range and angular distributions of these residues are discussed.

Table 3.2 List of reactions, identified γ-rays and their branching ratios.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Reaction</th>
<th>Residue</th>
<th>Eγ (keV)</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>169Tm(16O,3n)</td>
<td>182Ir</td>
<td>126.9, 273.1</td>
<td>34.4, 43</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>764.2, 891.1</td>
<td>5.6, 5.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>912.2</td>
<td>8.7</td>
</tr>
<tr>
<td>2.</td>
<td>169Tm(16O,4n)</td>
<td>181Ir</td>
<td>107.6, 123.5</td>
<td>15.2, 4.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>184.6, 227.0</td>
<td>4.2, 8.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>231.6, 318.9</td>
<td>4.6, 7.0</td>
</tr>
<tr>
<td>3.</td>
<td>169Tm(16O, pn)</td>
<td>183gOs</td>
<td>114.4, 381.8</td>
<td>20.7, 77</td>
</tr>
<tr>
<td>4.</td>
<td>169Tm(16O, p2n)</td>
<td>182Os</td>
<td>180.2, 263.3</td>
<td>34.7, 6.6</td>
</tr>
<tr>
<td>5.</td>
<td>169Tm(16O, p3n)</td>
<td>181gOs</td>
<td>238.7, 826.7</td>
<td>44, 20.2</td>
</tr>
<tr>
<td>6.</td>
<td>169Tm(16O, α)</td>
<td>181Re</td>
<td>360.7, 365.6</td>
<td>20, 57.0</td>
</tr>
<tr>
<td>7.</td>
<td>169Tm(16O, 2αp)</td>
<td>175Hf</td>
<td>343.4</td>
<td>87</td>
</tr>
<tr>
<td>8.</td>
<td>169Tm(16O, 2αp5n)</td>
<td>171Hf</td>
<td>122.0, 295.0</td>
<td>11.1, 4.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>662.0</td>
<td>9.2</td>
</tr>
<tr>
<td>9.</td>
<td>169Tm(16O, 3αn)</td>
<td>172gLu</td>
<td>1093.6</td>
<td>63.5</td>
</tr>
<tr>
<td>10.</td>
<td>169Tm(16O, 3α2n)</td>
<td>171gLu</td>
<td>739.8</td>
<td>48.1</td>
</tr>
</tbody>
</table>
3.2.1 The recoil range distributions at \( \approx 76 \) and 81 MeV

In the experiment performed to measure recoil range distributions a sample of \(^{169}\text{Tm} \) (\( \approx 47 \mu g/cm^2 \)) on \( \text{Al}-\text{backing} \) (\( \approx 1.1 \text{ mg/cm}^2 \)) was bombarded by \(^{16}\text{O} \) ion with \( \text{Al}-\text{backing} \) facing the beam. The sample was followed by a stack of \( \text{Al}-\text{catcher} \) foils of thickness ranging from \( \approx 20-60 \mu g/cm^2 \). The recoiling residues get trapped in the catcher foils at different ranges in \( \text{Al}-\text{catchers} \). Two such stacks were separately bombarded by \( \approx 76 \) and 81 MeV \(^{16}\text{O} \) beam. The activities induced in individual catcher foils were followed off-line. The residues embedded in different catcher foils were identified by their characteristic \( \gamma \) radiations and half lives. The cross-sections corresponding to various radioactive residues in each catcher were obtained from the intensity of identified \( \gamma \) rays. In this way, the cross-section for a particular evaporation residue in each catcher foil was determined. 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 foil. The results of recoil range distribution (RRD) measurements for \(^{16}\text{O} + ^{169}\text{Tm} \) system at \( \approx 76 \) and 81 MeV, are tabulated in Tables 3.2.1(a) and 3.2.1(b).
Table 3.2.1(a) Measured recoil range distributions (RRDs) for Ir, Os, Re, Hf and Lu isotopes at ≈76 MeV

<table>
<thead>
<tr>
<th>Cumulative thickness (μg/cm²)</th>
<th>182Ir</th>
<th>182Os</th>
<th>181Os</th>
<th>181Re</th>
<th>175Hf</th>
<th>171Hf</th>
<th>172Lu</th>
<th>171Lu</th>
</tr>
</thead>
<tbody>
<tr>
<td>20.6</td>
<td>-</td>
<td>144</td>
<td>337</td>
<td>63</td>
<td>38</td>
<td>34</td>
<td>49</td>
<td>475</td>
</tr>
<tr>
<td>42.3</td>
<td>-</td>
<td>1189</td>
<td>374</td>
<td>26</td>
<td>236</td>
<td>50</td>
<td>24</td>
<td>89</td>
</tr>
<tr>
<td>66.3</td>
<td>-</td>
<td>68</td>
<td>322</td>
<td>48</td>
<td>201</td>
<td>81</td>
<td>29</td>
<td>34</td>
</tr>
<tr>
<td>90.8</td>
<td>-</td>
<td>1489</td>
<td>352</td>
<td>40</td>
<td>134</td>
<td>104</td>
<td>869</td>
<td>39</td>
</tr>
<tr>
<td>117.8</td>
<td>-</td>
<td>97</td>
<td>378</td>
<td>46</td>
<td>217</td>
<td>187</td>
<td>929</td>
<td>46</td>
</tr>
<tr>
<td>145.9</td>
<td>267</td>
<td>138</td>
<td>345</td>
<td>42</td>
<td>216</td>
<td>94</td>
<td>55</td>
<td>71</td>
</tr>
<tr>
<td>174.5</td>
<td>293</td>
<td>133</td>
<td>380</td>
<td>121</td>
<td>617</td>
<td>231</td>
<td>815</td>
<td>84</td>
</tr>
<tr>
<td>203.1</td>
<td>600</td>
<td>254</td>
<td>514</td>
<td>491</td>
<td>335</td>
<td>59</td>
<td>235</td>
<td>126</td>
</tr>
<tr>
<td>232.5</td>
<td>1346</td>
<td>424</td>
<td>562</td>
<td>707</td>
<td>98</td>
<td>384</td>
<td>-</td>
<td>58</td>
</tr>
<tr>
<td>291.6</td>
<td>1864</td>
<td>805</td>
<td>752</td>
<td>712</td>
<td>544</td>
<td>256</td>
<td>-</td>
<td>44</td>
</tr>
<tr>
<td>322.3</td>
<td>1112</td>
<td>357</td>
<td>758</td>
<td>1629</td>
<td>324</td>
<td>57</td>
<td>-</td>
<td>226</td>
</tr>
<tr>
<td>353.3</td>
<td>500</td>
<td>-</td>
<td>394</td>
<td>1264</td>
<td>235</td>
<td>-</td>
<td>-</td>
<td>37</td>
</tr>
<tr>
<td>415.7</td>
<td>-</td>
<td>-</td>
<td>364</td>
<td>771</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>44</td>
</tr>
</tbody>
</table>
Table 3.2.1(b) Measured recoil range distributions (RRDs) for Ir, Os, Re, Hf and Lu isotopes at \( \approx 81 \text{ MeV} \)

<table>
<thead>
<tr>
<th>Cumulative thickness (( \mu g/cm^2 ))</th>
<th>( ^{182}\text{Ir} )</th>
<th>( ^{183}\text{Os} )</th>
<th>( ^{182}\text{Os} )</th>
<th>( ^{181}\text{Os} )</th>
<th>( ^{181}\text{Re} )</th>
<th>( ^{175}\text{Hf} )</th>
<th>( ^{171}\text{Hf} )</th>
<th>( ^{172}\text{Lu} )</th>
<th>( ^{171}\text{Lu} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>56.2</td>
<td>-</td>
<td>8</td>
<td>12</td>
<td>-</td>
<td>9</td>
<td>675</td>
<td>14</td>
<td>86</td>
<td>126</td>
</tr>
<tr>
<td>118.7</td>
<td>-</td>
<td>7</td>
<td>17</td>
<td>36</td>
<td>6</td>
<td>696</td>
<td>24</td>
<td>104</td>
<td>45</td>
</tr>
<tr>
<td>182.1</td>
<td>35</td>
<td>5</td>
<td>7</td>
<td>49</td>
<td>42</td>
<td>79</td>
<td>7</td>
<td>69</td>
<td>150</td>
</tr>
<tr>
<td>247.1</td>
<td>223</td>
<td>5</td>
<td>21</td>
<td>100</td>
<td>250</td>
<td>336</td>
<td>52</td>
<td>73</td>
<td>69</td>
</tr>
<tr>
<td>312.3</td>
<td>374</td>
<td>7</td>
<td>93</td>
<td>341</td>
<td>748</td>
<td>1008</td>
<td>101</td>
<td>58</td>
<td>263</td>
</tr>
<tr>
<td>378.3</td>
<td>586</td>
<td>19</td>
<td>138</td>
<td>484</td>
<td>1168</td>
<td>695</td>
<td>48</td>
<td>49</td>
<td>151</td>
</tr>
<tr>
<td>444.4</td>
<td>340</td>
<td>7</td>
<td>90</td>
<td>162</td>
<td>544</td>
<td>482</td>
<td>40</td>
<td>32</td>
<td>78</td>
</tr>
<tr>
<td>511.2</td>
<td>-</td>
<td>6</td>
<td>30</td>
<td>127</td>
<td>240</td>
<td>146</td>
<td>10</td>
<td>24</td>
<td>53</td>
</tr>
<tr>
<td>577.8</td>
<td>-</td>
<td>7</td>
<td>8</td>
<td>10</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>25</td>
<td>63</td>
</tr>
<tr>
<td>644.5</td>
<td>-</td>
<td>3</td>
<td>7</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>12</td>
<td>25</td>
<td>45</td>
</tr>
<tr>
<td>711.6</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>25</td>
<td>45</td>
</tr>
</tbody>
</table>
As may be observed from these tables, the recoil range distributions show peaking of cross-section at same cumulative catcher thickness. The measured RRDs are discussed in Chapter 5 of the thesis, where an attempt has also been made to obtain the relative contribution and energy dependence of CF and ICF components.

3.2.2 Measurement of angular distributions for the residues produced in $^{16}O + ^{169}Tm$ system at $\approx 81$ MeV

In the experiment performed to study angular distributions for the residues produced in the system $^{16}O + ^{169}Tm$, a sample of $^{169}Tm$ (on Al-backing) was irradiated by $\approx 81$ MeV $^{16}O^{7+}$ beam for 11 h. The details of the experimental setup are already given in Chapter 2 of the thesis. The outgoing residues were trapped in the annular catcher foils. The activities induced in the individual annular catcher foils were followed off-line. The residues were identified by their characteristic $\gamma$ radiations and half-lives. The identified $\gamma$-rays and their branching ratios are already given in Table 3.2. The cross-sections corresponding to various radioactive residues in each annular catcher have been computed using the intensities of identified $\gamma$ rays. In order to obtain the angular distributions, the measured cross-section for each evaporation residue has been plotted against angular range. The details of identified residues are given in the following,

1. $^{169}Tm(16O,3n)$ channel [$residue = ^{182}Ir$, $t_{1/2} = 15$ m]

2. $^{169}Tm(16O,4n)$ channel [$residue = ^{181}Ir$, $t_{1/2} = 4.9$ m, $J^\pi = 7/2^+$]
3. $^{169}\text{Tm}(^{16}\text{O},p2n)$ channel \([\text{residue} = ^{182}\text{Os}, t_{1/2}=21.6 \text{ h}, J^\pi = 0^+]\)

4. $^{169}\text{Tm}(^{16}\text{O},p3n)$ channel \([\text{residue} = ^{181}\text{Os}, t_{1/2}=1.75 \text{ h}, J^\pi = 1/2^-] \)

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

6. $^{169}\text{Tm}(^{16}\text{O},3\alpha n)$ channel \([\text{residue} = ^{172}\text{Lu}, t_{1/2}=6.7 \text{ d}, J^\pi = 4^-] \)

Experimentally measured cross-sections for above mentioned reaction channels for different angular ranges are tabulated in Table 3.2.2. Further, analysis and discussion on angular distributions are included in Chapter 5.

**Table 3.2.2 Measured angular distributions for six residues.**

<table>
<thead>
<tr>
<th>Angle-range</th>
<th>$\sigma(^{182}\text{Ir})$ (mb)</th>
<th>$\sigma(^{181}\text{Ir})$ (mb)</th>
<th>$\sigma(^{182}\text{Os})$ (mb)</th>
<th>$\sigma(^{181}\text{Os})$ (mb)</th>
<th>$\sigma(^{181}\text{Re})$ (mb)</th>
<th>$\sigma(^{172}\text{Lu})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^\circ - 13^\circ$</td>
<td>64±9</td>
<td>197±25</td>
<td>142±25</td>
<td>148±68</td>
<td>275±64</td>
<td>-</td>
</tr>
<tr>
<td>$13^\circ - 21^\circ$</td>
<td>1.0±0.2</td>
<td>2.1±0.3</td>
<td>3.2±0.5</td>
<td>3.5±0.5</td>
<td>6.1±2</td>
<td>-</td>
</tr>
<tr>
<td>$21^\circ - 30^\circ$</td>
<td>0.9±0.1</td>
<td>0.7±0.1</td>
<td>0.5±0.1</td>
<td>0.9±0.2</td>
<td>2.1±0.4</td>
<td>-</td>
</tr>
<tr>
<td>$30^\circ - 39^\circ$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.9±0.1</td>
<td>-</td>
</tr>
<tr>
<td>$39^\circ - 45^\circ$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.1±0.3</td>
<td>0.15±0.1</td>
</tr>
<tr>
<td>$45^\circ - 60^\circ$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.2±0.4</td>
<td>0.67±0.3</td>
</tr>
<tr>
<td>$60^\circ - 64^\circ$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.21±0.02</td>
<td>0.26±0.031</td>
</tr>
</tbody>
</table>

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References


Chapter 4

COMPUTER CODES AND MODEL
In the present work, theoretical calculations of the excitation functions have been performed using four different computer codes viz., ALICE-91[1], PACE[2], CASCADE[3] and SUMRULE[4]. Brief description of these codes are presented in the following.

4.1 ALICE-91

The code ALICE-91[1] is based on the Weisskopf-Ewing model[5] for compound nucleus reaction (equilibrium) while pre-equilibrium emission is simulated within the framework of Hybrid/Geometry Dependent Hybrid Model[6, 7]. In this code the possibility of incomplete fusion has not been taken into account but it can compute statistical fission cross-sections using Bohr-Wheeler approach with angular momentum dependent ground state and saddle point energies. The code considers the emission of neutrons, protons, deuterons and/or $\alpha$ particles. The code may calculate the reaction cross-sections for the residual nuclei upto 11 mass and 9 atomic number units away from the compound nucleus. Myers-Swiatecki/Lysekil mass formula[8] 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[9] subroutines. The transmission coefficients for heavy ions are calculated using the parabolic model of Thomas[10]. The pre-equilibrium 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 \( n_0 \) and the mean free path (MFP) multiplier \( COST \). The MFP for intranuclear transitions may be calculated from the optical model of Becchetti and Greenlees[11] or from Pauli corrected nucleon-nucleon cross-sections[12, 13]. 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 residues may be calculated either from the Fermi gas model or from the constant temperature form. The Fermi gas model gives[14],

\[
\rho(U) = (U - \delta)^{-5/4} e^{-\alpha(U - \delta)}
\]  \hspace{1cm} (32)

Where, \( \delta \) is the pairing term and \( U \) is the excitation energy of the nucleus. The level density parameter \( \alpha \) is taken as \( A/K \), where \( A \) being the mass number of the nucleus and \( K \) is an adjustable parameter. The level density \( \rho(U) \) in constant temperature approach is given as[15],

\[
\rho(U) \propto \frac{1}{T} e^{U/T}
\]  \hspace{1cm} (33)

The differential cross-section for emitting a particle with channel energy \( \epsilon \) may be written as (cross-section per unit energy to emit a particle of type \( \nu \) ),
\[
\frac{d\sigma}{d\varepsilon} = \frac{\lambda^2}{4\pi} \sum_{I=|I|}^{\infty} (2I + 1) T_I (2S_\nu + 1) \sum_{\ell=|\ell|}^{\infty} T^\ell_\nu(\varepsilon) \sum_{J=|J-\ell|}^{I+\ell} \rho(\varepsilon, J)/D \tag{34}
\]

Where, \( \lambda \) is the de-Broglie wavelength of the incident ion, \( T_I \) the transmission coefficient of the \( I^{th} \) partial wave of the incident ion, \( \rho(\varepsilon, J) \) 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 \( \nu \), \( T^\ell_\nu \) is the transmission coefficient for the particle \( \nu \) with kinetic energy \( \varepsilon \) and orbital angular momentum \( \ell \).

In the Weisskopf-Ewing calculations, the nuclear moment of inertia is assumed to be infinite and hence there is no energy tied to rotation. As such there is no level density cut off at high spin. This code does not take into account the angular momentum involved in heavy ion reactions. However, the heavy ion projectile imparts large angular momentum to the composite system which has a finite moment of inertia. Hence the composite nucleus has large rotational energy. Due to nuclear rotation, a nucleus with a given angular momentum \( J \), can not have energy below a minimum value \( E_J^{\text{min}} \), which is given by,

\[
E_J^{\text{min}} \approx J(J + 1) \frac{\hbar^2}{2I} \tag{35}
\]

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 γ emission, then, the peak of the excitation functions corresponding to particle emission mode will be shifted to higher energy[16]. 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. Assuming the excited nucleus to be rigid body, the rotational energy may be given by $E_{rot} \approx (m/M)E_{lab}$, where $m/M$ is the ratio of the projectile and target masses and $E_{lab}$ is the incident energy[16]. To account for the large angular momentum imparted to the composite system in heavy ion reactions, it is desirable to shift the energy axis for excitation functions calculated with code ALICE-91, by the approximate amount of the rotational energy $E_{rot}$.

4.2 PACE

The code PACE[2] is used to calculate the reaction cross-section of excited compound nucleus having high angular momentum using a statistical approach. In this code most of the required input parameters have been used as default. Fission is considered as a decay mode, while the incomplete fusion is not taken into account. The angular momentum conservation is explicitly taken into account at each step.

The partial cross-section for compound nucleus formation at angular momentum $\ell$ and specific bombarding energy is given by,
\[ \sigma_{t} = \frac{\pi \lambda^2}{4\pi^2} (2L + 1) T_{t} \]  

(36)

Where, \( \lambda \) is the reduced wavelength and \( T_{t} \) is given by,

\[ T_{t} = \left[ 1 + \exp\left(\ell - \ell_{\text{max}}\right)/\delta \right]^{-1} \]  

(37)

Where, \( \delta \) is the diffuseness parameter and \( \ell_{\text{max}} \) is obtained by total fusion cross-section,

\[ \sigma_{F} = \sum_{\ell = 0}^{\infty} \sigma_{t} \]  

(38)

The transmission coefficients for the evaporation of light particles (n, p and \( \alpha \)), 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[2]. 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 code PACE performs only the statistical equilibrium model calculations and does not take PE emission into consideration.

4.3 CASCADE

The code CASCADE[3] is based on Hauser-Feshbach theory[17] for compound nucleus calculations and is frequently used to calculate the reaction cross-sections for heavy-ion interactions. 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 product nuclei both stable and radioactive 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 for which 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 subroutines MASS and TLCALC, respectively, for the region of interest and are stored permanently on the disc. The optical model potentials of Becchetti and Greenlees [11] are used for calculating the transmission coefficients for protons and neutrons, while optical model potential of Satchler[18] 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[19],

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

(39)

Here, $T_t$ the transmission coefficient, depends on the energy and the orbital angular momentum. $S=(J_p + J_T)$ is the channel spin. The $T_t$ as a
function of angular momentum is approximated by a Fermi distribution,

\[ T_\ell = \frac{1}{1 + \exp[-(\ell - \ell_o)/d]} \]  

(40)

Where, \( \ell_o \) is the grazing angular momentum and \( d \) is the diffuseness parameter.

In case of even-even nuclei, the spins of the projectile and the target are taken as zero. The partial cross-section in that case is given as,

\[ \sigma_\ell = \frac{\lambda^2 (2\ell + 1) T_\ell(E)}{4\pi} \]  

(41)

While, the total cross-section \( (\sigma_t) \) is given by,

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

(42)

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

\[ \sigma_f = \frac{\pi \lambda^2}{4\pi^2} \sum_{\ell=0}^{\ell_c} (2\ell + 1) T_\ell(E) \]  

(43)

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

The level density \( \rho \) at an excitation energy \( E \) and spin \( J \) is given by[20],

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

(44)

with the level densities,

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

(45)
and the equation of state,

\[ U = E - \Delta = at^2 - \frac{3}{2}t \]  \hspace{1cm} (46)

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 \( aR = 2I/h^2 \), where, \( I \) is the effective moment of inertia obtained from the low lying states of the isotope. Generally, \( I \) is taken as,

\[ I = \frac{2}{5}mr^2 \]  \hspace{1cm} (47)

with, \( r = r_o A^{1/3} \)

The level density formula implies a yrast line,

\[ E_{\text{rot}}(J) = J(J+1)/aR + \Delta = \frac{J(J+1)h^2}{2I} + \Delta \]  \hspace{1cm} (48)

When large range of excitation energies are involved, the parameters used should be energy dependent. Therefore, the entire energy region is divided into three groups,

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 and Hillie et. al.,[21] and Dilg et. al.,[22].

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 $(1/8)A$ 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.[22] and (3) Ramamurthy et. al.[23]. The moment of inertia which determines the spin dependence is taken to be that of a deformable liquid drop with gyrostatic motion.

4.4 SUMRULE MODEL

The SUMRULE[4] model is based on idea of partial statistical equilibrium and generalized concept of critical angular momentum. With the help of this model, one can calculate absolute cross-sections for complete fusion, incomplete fusion and other binary reactions, which presumably proceed via the formation of dinuclear system. J.Wilczyński et.al.[4], assumed that the transfer of mass may only take place if the angular momentum of relative
The motion of the captured fragment with respect to the absorbing nucleus is smaller than the critical angular momentum \( \ell \leq \ell_{cr} \). The critical angular momentum \( \ell_{cr} \) (based on liquid drop model) is calculated with the help of the following formulation,

\[
\left( \ell_{cr} + \frac{1}{2} \right)^2 = \frac{\mu (C_1 + C_2)^3}{\hbar^2} \left[ 4 \pi \gamma \frac{C_1 C_2}{C_1 + C_2} - \frac{Z_1 Z_2 e^2}{(C_1 + C_2)^2} \right] \tag{49}
\]

Where, \( C_1, C_2 \) and \( Z_1, Z_2 \) are the half-density radii and charges of two interacting nuclei, respectively, while \( \gamma \) is the surface tension coefficient. The half-density radii may be calculated using the expression [24]

\[
C = R \left\{ 1 - \frac{\hbar^2}{R^2} + \ldots \right\} \tag{50}
\]

Where, \( b = 1 \) fm and \( R = (1.28A^{\frac{1}{3}} - 0.76 + 0.8A^{\frac{1}{3}}) \) fm. The surface tension coefficient \( \gamma \) is given as,

\[
\gamma = 0.95(1 - 1.78I^2) \text{MeV.fm}^2 \tag{51}
\]

As concluded by Bondorf et.al.[25], the reaction probability for a given channel \( P(i) \) is proportional to the following exponential factor,

\[
P(i) \propto \exp \left( \frac{Q_{gg}(i) - Q_{C}(i)}{T} \right) \tag{52}
\]

Where, \( Q_{gg} \) is the ground state Q-value, \( T \) the effective temperature and \( Q_{C}(i) = (Z_b Z_Y - Z_a Z_X)e^2/R_C \) is the change in the Coulomb interaction energy due to the transfer of charge. \( Z_a, Z_X, Z_b \) and \( Z_Y \) are, respectively, the charges of the initial ions and of the final ions.
Under the assumption of the smooth cut-off in the $\ell$ space for each individual reaction channel $i$, the transmission coefficient $T_{t}(i)$ is given as,

$$T_{t}(i) = \left[1 + \exp\left(-\frac{\ell - \ell_{\text{lim}}(i)}{\Delta}\right)\right]^{-1} \tag{53}$$

Here, $\ell_{\text{lim}}(i)$ is the limiting angular momentum in the reference frame of entrance channel and $\Delta$ the diffuseness of the cut-off in the $T_{t}$ distribution, respectively.

The absolute cross-section for a reaction channel $i$ is given by the expression,

$$\sigma(i) = \pi \lambda^{2} \sum_{\ell=0}^{\ell_{\text{max}}} (2\ell + 1) \frac{T_{t}(i)P(i)}{\sum_{j} T_{t}(j)P(j)} \tag{54}$$

Where, $\lambda = \frac{\hbar}{2\mu E}$ is the reduced wave length associated with the entrance channel in the center of mass system and $\ell_{\text{max}}$ is the angular momentum that confines the range of partial waves leading to formation of the dinuclear system.

The model contains three free parameters, one is the effective temperature $T$, second the effective Coulomb interaction radius $R_{C}$ and the third is diffuseness $\Delta$ of the $T_{t}$ distributions. The second and third parameters are purely empirical in nature, while $T$ has no clear interpretation.
References


RESULTS AND DISCUSSION
In the present work, excitation functions (EFs) for twenty three reactions have been measured. A list of these reactions is given below:

\[ ^{128}\text{Te}(^{14}N,4n)^{138m}\text{Pr}, \quad ^{128}\text{Te}(^{14}N,5n)^{137}\text{Pr}, \quad ^{128}\text{Te}(^{14}N,p4n)^{137}\text{Ce}, \]
\[ ^{128}\text{Te}(^{14}N,\alpha 5n)^{133}\text{La}, \quad ^{128}\text{Te}(^{14}N,\alpha 6n)^{132}\text{La}, \quad ^{128}\text{Te}(^{14}N,\alpha 2pn)^{135}\text{mCs}, \]
\[ ^{128}\text{Te}(^{14}N,2\alpha 2pn)^{131}\text{I}, \quad ^{128}\text{Te}(^{14}N,3\alpha)^{130}\text{I}, \quad ^{103}\text{Rh}(^{16}O,\alpha)^{117}\text{Te}, \]
\[ ^{103}\text{Rh}(^{16}O,p2n)^{116}\text{Te}, \quad ^{103}\text{Rh}(^{16}O,2p)^{117}\text{Sb}, \quad ^{103}\text{Rh}(^{16}O,2pn)^{116}\text{Sb}, \]
\[ ^{103}\text{Rh}(^{16}O,2\alpha 2pn)^{110}\text{mSb}, \quad ^{103}\text{Rh}(^{16}O,\alpha)^{115}\text{Sb}, \quad ^{103}\text{Rh}(^{16}O,2\alpha)^{118}\text{In}, \]
\[ ^{103}\text{Rh}(^{16}O,2\alpha 2n)^{109}\text{mIn}, \quad ^{103}\text{Rh}(^{16}O,3\alpha n)^{106}\text{mAg}, \quad ^{103}\text{Rh}(^{16}O,3\alpha 3n)^{104}\text{Ag}, \]
\[ ^{130}\text{Te}(^{16}O,5n)^{141}\text{Nd}, \quad ^{130}\text{Te}(^{16}O,\alpha 3n)^{139}\text{Ce}, \quad ^{130}\text{Te}(^{16}O,3\alpha n)^{133}\text{mXe} \] and \[ ^{130}\text{Te}(^{16}O,3\alpha 3n)^{131}\text{mXe}. \]

The measured EFs for these reactions are plotted in Figs. 5.1.1-5.3.3. The analysis of EFs has been performed employing three different computer codes viz., ALICE-91[1], PACE[2] and CASCADE[3]. Details of the analysis are provided in Sections 5.1 to 5.3.

With a view to separate out the relative contributions of complete fusion (CF) and incomplete fusion (ICF), the recoil range distributions (RRDs) of some residues produced in the interaction of \(^{16}O\) with \(^{169}Tm\) have been measured at \(\approx 76\) and \(81\) MeV energies. The RRD for the radioactive residues of reactions \(^{169}Tm(^{16}O,3n)^{182}\text{Ir}, \quad ^{169}Tm(^{16}O,pn)^{183}\text{mOs}, \] \[ ^{169}Tm(^{16}O,p2n)^{162}\text{Os}, \quad ^{169}Tm(^{16}O,p3n)^{181}\text{mOs}, \quad ^{169}Tm(^{16}O,\alpha)^{181}\text{Re}, \]
\[ ^{169}Tm(^{16}O,2\alpha pn)^{175}\text{Hf}, \quad ^{169}Tm(^{16}O,2\alpha p5n)^{171}\text{Hf}, \quad ^{169}Tm(^{16}O,3\alpha n)^{172}\text{mLu} \] and \(^{169}Tm(^{16}O,3\alpha 2n)^{171}\text{mLu}\) have been measured. The analysis of the
data is presented in section 5.5. An attempt has also been made to measure the angular distributions of radioactive residues formed in the reactions $^{169}Tm(^{16}O,3n)^{182}Ir$, $^{169}Tm(^{16}O,4n)^{181}Ir$, $^{169}Tm(^{16}O,p2n)^{182}Os$, $^{169}Tm(^{16}O,p3n)^{181}Os$, $^{169}Tm(^{16}O,\alpha)^{181}Re$ and $^{169}Tm(^{16}O,3\alpha n)^{172}Lu$ at $\approx81$ MeV incident beam energy. Detailed analysis of these measurements is presented in section 5.6.

**5.1 Analysis using code ALICE-91**

The code ALICE-91 developed by M. Blann[4], is based on Weisskopf-Ewing model[5] for CN calculations and Hybrid Model[6] for simulating PE-emission. The code assumes equipartition of energy among the initially excited particles and holes. It uses Gove mass tables[7] or Myers Swiatecki/Lysekil[8] mass formula. The option that substitutes Gove's table[7] for Myers Swiatecki/ Lysekil[8] mass formula including shell corrections has been used. In order to calculate inverse cross-sections optical model subroutine with the parameters of Becchetti and Greenlees[9] has been employed for the reaction channels occurring in the systems $^{14}N + ^{128}Te$, $^{16}O + ^{103}Rh$ and $^{16}O + ^{130}Te$. The measured EFs for various channels populated in these systems are compared with those of theoretical predictions in Figs. 5.1.1 to 5.1.7.

**System ($^{14}N + ^{128}Te$)**

The important parameters of the code ALICE-91 are the level density parameter $\alpha$, initial exciton number $n_o$, and the mean free path multi-
plier $COST$. The first parameter largely affects the equilibrium component, through the level densities. The level density parameter $a$ is calculated using the relation $a = A/K$, where $A$ is the mass number of the nucleus and $K$ is a constant which may be varied to match the experimental data. The effect of the variation of $K$ on the calculated EFs has been studied. The value of $K$ was varied from 9 to 18. As a typical example the calculated EFs for the reaction $^{126}\text{Te}(^{11}\text{N}, 4n)$ for different values of $K$ are shown in Fig. 5.1.1. As can be seen from this figure and, in general, the present experimental data is best reproduced with a value of $K=18$. However, it has been pointed out by J.P. Leston[10] that the value of $K$ above 10 is unrealistic.

![Excitation functions for the reaction $^{126}\text{Te}(^{11}\text{N}, 4n)^{138n}\text{Pr}$](image)

**Fig. 5.1.1** Excitation functions for the reaction $^{126}\text{Te}(^{11}\text{N}, 4n)^{138n}\text{Pr}$. The filled circles represent the experimental data. Various curves correspond to the theoretical predictions of the code ALICE-91.
Hence, the calculations done using the level density parameter $K=9$ and 10 are shown in Fig. 5.1.2(a).

The parameters $n_0$ and $COST$ largely govern the PE-component. The initial exciton number $n_0$ decides the complexity of initial configuration. Smaller value of $n_0$ means that the initial state is less complex and hence far from the equilibrium. As such, a larger PE-contribution is expected. On the other hand a large value of $n_0$ means that the system is nearer to the equilibrium stage and therefore, smaller PE-contribution is likely. In order to study the effect of variation of $n_0$ on calculated EFs, calculations have been done by varying $n_0$ from 14 to 16\[11\]. As a representative case, these calculations for $^{12}\text{Be}')(^{14}N,4n)$ channel are shown in Fig. 5.1.2(b). It may be seen from this figure, and in general also, that a value of $n_0=14$ is best suited for the present experimental data. A value of $n_0=14$ may be justified assuming that the projectile $^{14}N$ breaks up in the nuclear field of the target nucleus creating 14 excitons. The parameter $COST$, which may be used to adjust the mean free path for two body residual interactions inside the nuclear matter is varied from 1 to 3 and its effect on excitation function for $^{12}\text{Be}')(^{11}N,3n)$ reaction is shown in Fig. 5.1.2(c), as a representative case. It may be pointed out that a set of $K=10$, $n_0=14$ with $COST=3$ gives a satisfactory reproduction of the magnitude of the experimental data, in general. As a typical case, the calculated excitation function for $^{12}\text{Be}')(^{11}N,5n)$ reaction is shown in Fig. 5.1.2.(d) along with the measured data. It may be observed that the theoretical calculations satisfactorily reproduce the magnitude of the experimental data in the peak region.
Fig. 5.1.2 Excitation functions for the reactions $^{128}\text{Te}^{(14\text{N}, 4\text{n})^{138m}\text{Pr}}$, $^{128}\text{Te}^{(14\text{N}, 5\text{n})^{137}\text{Pr}}$ and $^{128}\text{Te}^{(14\text{N}, p4\text{n})^{137g}\text{Ce}}$. The filled circles represent the experimental data. Various curves correspond to the theoretical predictions of the code ALICE-91.
It has, however, been observed that excitation functions calculated using the above set of parameters for all the cases studied presently, have their maxima shifted towards the lower energy side, as compared to the experimental data. This is expected as in HI induced reactions, the projectile imparts large angular momentum to the composite system. As such, this high angular momentum imparted to the composite system, may inhibit particle emission in the last stages of de-excitation\[13\]. As a result, the peaks of the experimental EFs corresponding to particle emission mode are expected to be shifted towards higher energy\[13\] side. This effect has not been taken into account in code ALICE-91. An estimate of the possible energy shift may be obtained from the rotational energy $E_{rot}$, which may be approximated using the formulation $E_{rot} \approx (m/M)E_{lab}[13]$, where, $m$ and $M$ are respectively the projectile and target masses and $E_{lab}$ is incident energy. In the regime of incident energies considered in the present work, the rotational energy shift ($E_{rot}$) for different systems is found to vary from $\approx 7$ to $9 \text{ MeV}$. Since, the angular momentum effects have not been taken into account in Weisskopf-Ewing calculations, it is desirable to shift the calculated EFs by an amount $\approx E_{rot}$. As such, theoretically calculated EFs for all the reactions were shifted towards the higher energy side by an amount $\approx E_{rot}$ and satisfactory agreement between experimental and theoretical EFs has been observed, in general. As a representative case the effect of rotational energy on calculated EF for the reaction $^{128}Te(^{14}N, 4n)$ is shown in Fig. 5.1.2.(e).

In Fig. 5.1.2.(f), experimentally measured cross-sections for the reaction $^{128}Te(^{14}N, p4n)$ are shown along with theoretically calculated EFs. As can
be seen from this figure, even by varying the level density parameter constant $K$, the theoretical calculations underestimate the cross-sections as compared to the experimental data. These larger values of observed cross-sections may be due to the contribution from precursor decay. During irradiation of the sample, the residual nucleus $^{137}Ce$ may be populated via two different channels. One, directly through the reaction $^{128}Te(^{4}N,p4n)$ and secondly through the $\beta^{+}$/EC decay of the residual nucleus $^{137}Pr$ formed via the reaction $^{128}Tr(^{14}N,5n)$. As such, the measured cross-sections of $^{128}Te(^{4}N,p4n)$ reaction will have contribution from the $\beta^{+}$ decay of higher charge isobar precursor (cumulative yield) also. Though, it is possible to estimate the contribution from precursor decay[14], however this could not be done in the present case, since the meta stable state of the $^{137}Ce$ could not be observed.

In figure 5.1.3(a), experimentally measured EF for $^{128}Te(^{4}N,4n)$ reaction is compared with the theoretical calculations done using only the CN model as well as by including PE-component. The dashed line in this figure shows CN calculations done by considering Weisskopf-Ewing model. As can be seen from this figure, the CN calculations do not match with the experimental data in the higher energy side where PE-emission may be important. In order to see the effect of PE-emission theoretical calculations were also performed using hybrid model option of the code ALICE-91. It can be see from Fig. 5.1.3(a), that high energy tail portion of the measured EF is close to calculated EF, if PE-emission is included in the calculations. As such, it may be concluded that there is considerable PE-component in the
Fig. 5.1.3 Excitation functions for the reactions $^{128}\text{Te}(^{14}\text{N}, 4\alpha)^{138m}\text{Pr}$, $^{128}\text{Te}(^{14}\text{N}, \alpha 5\alpha)^{133}\text{La}$, $^{128}\text{Te}(^{14}\text{N}, \alpha 6\alpha)^{132g}\text{La}$, $^{128}\text{Te}(^{14}\text{N}, \alpha 2\alpha\text{pn})^{135m}\text{Cs}$, $^{128}\text{Te}(^{14}\text{N}, 2\alpha 2\text{pn})^{131}\text{I}$ and $^{128}\text{Te}(^{14}\text{N}, 3\alpha)^{130g}\text{I}$. The filled circles represent the experimental data. The solid and dotted lines correspond to the theoretical predictions of the code ALICE-91, respectively.
reaction $^{128}Te(^{14}N, 4\alpha n)$ at higher energies, as expected. For $^{128}Te(^{14}N, 5\alpha n)$ and $^{128}Te(^{14}N, 6\alpha n)$ reactions, the theoretical predictions of code ALICE-91 including PE-emission give substantially small cross-sections as compared to the measured cross-sections as shown in Figs. 5.1.3(b) and (c) respectively. This discrepancy of considerably higher values of the experimentally measured cross-sections as compared to the theoretical calculations, may be explained in terms of the contribution coming from ICF of the $^{14}N$ ion. If it is assumed that $^{14}N$ ion breaks up into $^{10}B$ and $^4He$ fragments under the nuclear field of the target nucleus and if only one of the two fragments i.e., $^{10}B$ fuses with the target (and $^4He$ moves along the beam direction) nucleus forming the excited composite system $^{138}La^*$. The excited $^{138}La^*$ may then emit $5n/6n$ leading to the formation of the residual nuclei $^{133}La$ and $^{132}La$, respectively. Theoretical calculations of ALICE-91, however, do not take into account this ICF process. As such, the discrepancy in the experimentally measured EFs and the theoretically calculated counterparts may be attributed to the above mentioned ICF processes.

For the $^{128}Te(^{14}N, 2\alpha 2pn)$, $^{128}Te(^{14}N, 2\alpha 2pn)$ and $^{128}Te(^{14}N, 3\alpha)$ reactions, theoretical predictions of code ALICE-91 give negligible cross-sections. However, the measured cross-sections are substantial as shown in figure 5.1.3(d-f). This discrepancy of much higher experimentally measured cross-sections as compared to the theoretical calculations, may again indicate the presence of contributions coming from incomplete fusion of the $^{14}N$ ion. The higher cross-sections in case of $^{128}Te(^{14}N, 2\alpha 2pn)$ reaction may be explained assuming that $^{10}B$ (If $^{14}N$ breaks up into $^{10}B$ and $^4He$) fuses with the target.
nucleus emitting two protons and a neutron. Similarly, in case of the reac-
tion $^{128}\text{Te}^{(14N, 2\alpha 2pn)}$ it may be assumed that $^{14N}$ breaks into $^{6}\text{Li}$ and two alpha particles, where $^{6}\text{Li}$ fuses with the target nucleus to form $^{134}\text{Cs}^*$. The excited composite system $^{134}\text{Cs}^*$ then emits two protons and one neutron to produce $^{131}\text{I}$. Further, in case of $^{128}\text{Te}^{(14N, 3\alpha)}$ reaction, it may be assumed that the $^{14N}$ breaks up into three $\alpha$-particles and a deuteron, where fusion of deuteron takes place with target nucleus leaving behind the residual nucleus $^{131}\text{I}$ which may decay by $\gamma$-emission. Since, excitation functions calculated using ALICE-91 (which does not include incomplete fusion) underestimate the measured data for $^{128}\text{Te}^{(14N, 5\alpha n)}$, $^{128}\text{Te}^{(14N, 6\alpha n)}$, $^{128}\text{Te}^{(14N, 2\alpha 2pn)}$, $^{128}\text{Te}^{(14N, 2\alpha 2pn)}$ and $^{128}\text{Te}^{(14N, 3\alpha)}$ reactions, it may be inferred that incomplete fusion contributes significantly to these reactions.

**System ($^{16O + ^{103}Rh}$)**

In all the calculations done for the reactions induced in the interaction of $^{16O + ^{103}Rh}$, a value of $K=10$ gives satisfactory reproduction of the experimental data. The value of $n_0$ is taken as 16, which may be justified assuming that the projectile $^{16O}$ breaks up in the nuclear field of the target nucleus creating 16 excitons. The parameter $\text{COST}$, which is used to adjust the mean free path for two body residual interactions inside the nuclear matter, is taken equal to 3. It may be pointed out that a set of $K=10$, $n_0=16$ with $\text{COST}=3$ gives a satisfactory reproduction of the magnitude of the experimental data. In Fig. 5.1.4, experimentally measured EF for $^{103}\text{Rh}^{(16O, pn)}$ reaction is compared with the theoretical calculations done with the inclusion of PE-emission to the CN calculations. It can be seen from this figure, that
Fig. 5.1.4 Excitation functions for the reaction $^{103}$Rh($^{16}$O, pn)$^{117}$Te. The filled circles represent the experimental data. Theoretical predictions of code ALICE-91, with and without pre-equilibrium emission are shown by solid and dotted lines, respectively.

The high energy tail portion of the measured EF is close to calculated EF, if PE-emission is included in the calculations. As such, it may be concluded that PE-emission plays an important role at higher energy regime, as expected. In Figs. 5.1.4, 5.1.5(a), (b) and (c) the measured EFs for the reactions $^{103}$Rh($^{16}$O, pn), $^{103}$Rh($^{16}$O, p2n), $^{103}$Rh($^{16}$O, 2p) and $^{103}$Rh($^{16}$O, 2pn) are shown alongwith calculated EFs. From these figures, it may be observed that the theoretical calculations give lower cross-section values as compared to the experimental data. These higher values of observed EFs may again be due to the contribution from precursor decay, as discussed below.
During irradiation of the sample, residues $^{117}\text{Te}$ and $^{116}\text{Te}$ may be populated via two different channels. One, directly through the reactions $^{103}\text{Rh}^{(16}\text{O},pn)$ & $^{103}\text{Rh}^{(16}\text{O},p2n)$, respectively and secondly, through the $\beta^+$/EC decay of higher charge isobar precursors $^{117}\text{I}$ and $^{116}\text{I}$ formed via the reactions $^{103}\text{Rh}^{(16}\text{O},2n)$ and $^{103}\text{Rh}^{(16}\text{O},3n)$, respectively. As such, the measured activities of $^{117g,116}\text{Te}$ may have contributions from the $\beta^+$/EC decay of higher charge isobar precursors (cumulative yield) also. It is possible to separate out the contribution from precursor decay using successive radioactive decay formulations [14]. In the present case, the precursors $^{117}\text{I}(t_{1/2} = 2.2 \text{ m})$ and $^{116}\text{I}(t_{1/2} = 2.9 \text{ sec})$ have short half lives, and could not be observed, since counting could be started only after 10 m of the stop of the irradiation. However, for separating the precursor contribution the values of cross-sections for the production of residues $^{117}\text{I}$ and $^{116}\text{I}$ have been taken from the predictions of code PACE. The independent yields (filled symbols) of $^{117g}\text{Te}$ and $^{116}\text{Te}$ obtained after subtracting the precursor contributions are also shown in Fig. 5.1.4 and 5.1.5(a), along with cumulative yields (open symbols). As can be seen from this figure, that now there is some what better agreement between theoretical and measured excitation functions. Similarly, in case of reaction $^{103}\text{Rh}^{(16}\text{O},2p)$ the residue $^{117}\text{Sb}$ may be populated (i) directly through 2p channel and (ii) via the decay of higher charge isobar precursor $^{117g}\text{Te}$ formed in the $^{103}\text{Rh}^{(16}\text{O},pn)$ reaction. The precursor contribution in this case has also been separated using the prescription given by Cavinato et.al., [14]. The cumulative as well as independent yields as obtained from the decay analysis have been plotted in Fig. 5.1.5(b). Theoretical calculations of code ALICE-91 though show much lower cross-sections but follow the same trend as that
of measured values. Experimentally measured reaction cross-sections for the reactions $^{103}\text{Rh}(^{16}\text{O}, 2\text{pn})^{116}\text{Te}$, $^{103}\text{Rh}(^{16}\text{O}, 2\text{p})^{117}\text{Sb}$, $^{103}\text{Rh}(^{16}\text{O}, 2\text{pm})^{116}\text{Sb}$, $^{103}\text{Rh}(^{16}\text{O}, 2\text{pn})^{116\text{m}}\text{Sb}$ and $^{103}\text{Rh}(^{16}\text{O}, \alpha)^{115}\text{Sb}$. Theoretical predictions of code ALICE-91 are shown by solid lines.

Fig. 5.1.5 Excitation functions for the reactions $^{103}\text{Rh}(^{16}\text{O}, 2\text{pn})^{116}\text{Te}$, $^{103}\text{Rh}(^{16}\text{O}, 2\text{p})^{117}\text{Sb}$, $^{103}\text{Rh}(^{16}\text{O}, 2\text{pm})^{116}\text{Sb}$, $^{103}\text{Rh}(^{16}\text{O}, 2\text{pn})^{116\text{m}}\text{Sb}$ and $^{103}\text{Rh}(^{16}\text{O}, \alpha)^{115}\text{Sb}$. Theoretical predictions of code ALICE-91 are shown by solid lines.
It may, however, be noted that ALICE-91, calculations give only the total cross-sections and do not calculate cross-sections for isomeric and ground states separately. The independent yield for $^{118}\text{Sb}$ has been separated from the measured cumulative yield using the standard formulation of successive radioactive decay.

The enhancement of measured excitation functions for the reactions $^{103}\text{Rh}^{(16}O,\alpha)^{115}\text{Sb}$, $^{103}\text{Rh}^{(16}O,2\alpha)^{111}\text{In}$ and $^{103}\text{Rh}^{(15}O,2\alpha2n)^{109}\text{In}$ as shown in Figs. 5.1.5(d), 5.1.6(a) and (b), may be attributed to the fact that these residues may not only be populated by the complete fusion alone but also have significant contributions from incomplete fusion. The residue $^{115}\text{Sb}$ may be produced via two different channels. One, by the complete fusion of $^{16}O$ with $^{103}\text{Rh}$ forming $^{119}\text{I}$ and secondly, by the emission of an $\alpha$-particle from this composite system. The residue $^{115}\text{Sb}$ may also be populated through ICF process, if it is assumed that the incident $^{16}O$ ion breaks up into $^{12}C$ and an $\alpha$-particles out of which, $^{12}C$ fuses with $^{103}\text{Rh}$ target nucleus giving rise to the formation of $^{115}\text{Sb}$, which may decay by emitting $\gamma$ radiations. Similarly, in case of the reaction $^{103}\text{Rh}^{(16}O,2\alpha)$, the residue $^{119}\text{In}$ may be populated both via CF & ICF channels. Here, it may be assumed that $^{16}O$ breaks up into $^{8}\text{Be}$ and $2\alpha$ fragments in the field of the interacting ions, where $^{8}\text{Be}$ fuses with the target nucleus and $2\alpha$-particles move forward. Since, code ALICE-91 do not take into account this incomplete fusion process, as such, the enhancement of experimentally measured excitation functions in comparison with theoretically calculated counter parts may be attributed to the incomplete fusion processes. The excitation function
Fig. 5.1.6 Excitation functions for the reactions \(^{103}\text{Rh}(^{16}\text{O}, 2\alpha)^{111}\text{In}\), \(^{103}\text{Rh}(^{16}\text{O}, 2\alpha 2n)^{109}\text{In}\), \(^{103}\text{Rh}(^{16}\text{O}, 3\alpha n)^{106m}\text{Ag}\) and \(^{103}\text{Rh}(^{16}\text{O}, 3\alpha 3n)^{104}\text{Ag}\).

Theoretical predictions of code ALICE-91 are shown by solid lines.

The reaction \(^{16}\text{Rh}(^{16}\text{O}, 2\alpha 2n)^{109}\text{In}\) needs special mention. In this case, the metastable states of half lives 1.3 m and 0.2 sec of \(^{109}\text{In}\) could not be observed. As such, the discrepancy may be attributed to the contri-
bution from metastable state as well as from the incomplete fusion process. Further, the theoretical calculations give negligible cross-sections in comparison to measured cross-sections for the reactions $^{103}Rh(^{16}O,3\alpha n)^{106m}Ag$ and $^{103}Rh(^{16}O,3\alpha 3n)^{104g}Ag$, while, the experimental values are quite substantial as shown in Fig. 5.1.6(c) and (d). As such, it may again be inferred that major contributions for the production of these residual nuclei may come from ICF (if $^{16}O$ breaks up into $\alpha$ and $^{12}C$ fragments) channels, which are not considered in these calculations. The reaction $^{103}Rh(^{16}O,3\alpha n)^{106m}Ag$ may be explained assuming that incident $^{16}O$ ions breaks up into $\alpha$-particle & $^{12}C$ and one of the fragments i.e., $\alpha$-particle fuses with the target nucleus forming composite system $^{107}Ag$, which may emit a neutron leaving behind the residue $^{106m}Ag$. Similarly, the reaction $^{103}Rh(^{16}O,3\alpha 3n)^{104g}Ag$, may be explained if three neutrons are emitted from the composite system $^{107}Ag$ formed by the fusion of $\alpha$-particle with $^{103}Rh$. 

System ($^{16}O + ^{130}Te$) 

The measured EFs for the reactions produced in the $^{16}O + ^{130}Te$ system have also been compared with theoretical predictions based on computer code ALICE-91. As a typical example the effect of the variation of parameter $K$ on the calculated EFs for $^{130}Te(^{16}O,5n)^{141g}Nd$ reaction has been shown in Fig. 5.1.7(a). The present experimental data is best reproduced with a value of $K = 10$. In order to see the effect of variation of $n_0$ on calculated EFs, calculations have been done by varying $n_0$ from 14 to 16 in steps of one. The value of $n_0=16$ is best suited for the present experimental data as in case of $^{16}O + ^{103}Rh$ system. The parameter $COST$ is also varied from 1 to 3 and
Fig. 5.1.7 Excitation functions for the reactions $^{130}Te(^{16}O, 5n)^{141}Nd$, $^{130}Te(^{16}O, 3n)^{139}Ce$, $^{130}Te(^{16}O, 3\alpha n)^{133}Xe$, $^{130}Te(^{16}O, 3\alpha n)^{133m}Xe$ and $^{130}Te(^{16}O, 3\alpha 3n)^{131m}Xe$. The symbols are representing the experimental data and theoretical calculations using code ALICE-91 are shown by various lines.

the value of $COST=1$ reproduces the experimental data satisfactorily. For this system the rotational energy shift is calculated to be $\approx 7.5$ to $11$ MeV. In case of $^{130}Te(^{16}O, \alpha 3n)$ reaction, theoretical predictions of code give low cross-sections while the measured experimental cross-sections are substantial.
as shown in Fig. 5.1.7(b). This discrepancy of much higher experimentally measured cross-sections as compared to the theoretical calculations, may be explained in terms of the contribution coming from ICF of the $^{16}O$ ion. If it is assumed that $^{16}O$ ion breaks up into $^{12}C$ and $^4He$ fragments under the nuclear field of the target nucleus and if $^{12}C$ of the two fragments fuses with the target nucleus and reaming part of it moves in the beam direction as a spectator.

In Figs. 5.1.7(c) and (d) measured cross-sections for the reactions $^{130}Te(^{16}O,3\alpha 3n)$ and $^{130}Te(^{16}O,3\alpha 3n)$ have been shown. In case of these reactions, calculations give negligible cross-sections while the measured experimental cross-sections are quite substantial as shown in figures. Since, ICF is not considered in these calculations the enhancement of the measured EFs for these reactions may be attributed to the contributions from ICF Channels.

### 5.2 Analysis using code PACE

The code PACE[2] 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. Measured and calculated excitation functions for the reaction residues populated in the systems $^{14}N + ^{128}Te$, $^{16}O + ^{103}Rh$ and $^{16}O + ^{130}Te$ are graphically shown in Figs 5.2.1 to 5.2.5 and are discussed here.
System \(^{(14N + ^{128}Te)}\)

In code PACE the level density parameter \(a\) is an important parameter, which may be varied to match the experimental data. The effect of variation in level density parameter constant \(K(=8, 9\) and \(10)\) on calculated EFs for the reactions \(^{128}Te(^{14}N, 4n)\), \(^{128}Te(^{14}N, 5n)\) and \(^{128}Te(^{14}N, 4p4n)\) are shown in Figs. 5.2.1(a-c). As can be observed from these figures, a value of \(K=9\) satisfactorily reproduces the measured EFs for \(^{128}Te(^{14}N, 4n)\) and \(^{128}Te(^{14}N, 5n)\) channels which are populated via complete fusion. Further, as can be seen from Fig. 5.2.1(c), that the experimental values are larger as compared to their theoretical counter part. As in case of ALICE-91 calculations also, it may be because of the contribution from precursor decay. As already mentioned the precursor contribution in this case could not be separated. Since, ICF is not considered in these calculations the enhancement of the measured EFs over their theoretical counter part for reactions \(^{128}Te(^{14}N, \alpha 5n)\) and \(^{128}Te(^{14}N, \alpha 6n)\) as shown in Figs. 5.2.1(d) & (e) may be attributed to the fact that these isotopes are not only produced by the complete fusion but also have significant contribution from ICF (if \(^{14}N\) breaks up into \(^{10}B\) and \(^{4}He\) fragments). Further, the theoretical PACE calculations give negligible cross-sections for the reactions \(^{128}Te(^{14}N, \alpha 2pn)\), \(^{128}Te(^{14}N, 2\alpha 2pn)\), and \(^{128}Te(^{14}N, 3\alpha)\) while the experimental values are quite substantial as shown in Figs. 5.2.1(f), 5.2.2(a) & (b), respectively. As such, it may again be inferred that major contribution for the production of these residues comes from ICF channels, which are not considered in these calculations.
Fig. 5.2.1 Excitation functions for the reactions $^{126}\text{Te}^{(14}N,4n)^{138m}\text{Pr}$, $^{126}\text{Te}^{(14}N,5n)^{137}\text{Pr}$, $^{128}\text{Te}^{(14}N,p4n)^{137g}\text{Ce}$, $^{126}\text{Te}^{(14}N,\alpha5n)^{133}\text{La}$, $^{128}\text{Te}^{(14}N,\alpha6n)^{132g}\text{La}$ and $^{128}\text{Te}^{(14}N,\alpha2pn)^{135m}\text{Cs}$. The filled circles represent the experimental data. Various curves correspond to the theoretical predictions of the code PACE.
Fig. 5.2.2 Excitation functions for the reactions $^{128}\text{Te}^{(^{14}\text{N}, 2\alpha 2\text{pn})^{131}\text{I}}$ and $^{128}\text{Te}^{(^{11}\text{N}, 3\alpha)^{130}\text{I}}$. The filled circles represent the experimental data.
System \((^{16}O + ^{103}Rh)\)

In the present calculations for the reactions populated in \(^{16}O + ^{103}Rh\) system, a value of \(K=9\) is found to give a satisfactory reproduction of experimental data. In Figs. 5.2.3(a), (b), (c) and (d), experimentally measured cross-sections for the reactions \(^{103}Rh(^{16}O, pn)\), \(^{103}Rh(^{16}O, p2n)\), \(^{103}Rh(^{16}O, 2p)\) and \(^{103}Rh(^{16}O, 2pn)\) are shown along with theoretically calculated EFs. As can be seen from these figures, theoretical calculations underestimate the cross-sections as compared to the experimental data. These larger values of observed cross-sections may be due to the contribution from the decay of higher charge precursor, as discussed in section 5.1. As shown in Figs. 5.2.3(e) and (f), in case of channels \(^{103}Rh(^{16}O, \alpha)^{115}Sb\) and \(^{103}Rh(^{16}O, 2\alpha)^{111}In\), the measured cross-sections exceed the theoretical calculations. This discrepancy may be attributed to the fact that these channels are populated not only by complete fusion but also by ICF process (i.e., fusion of \(^{12}C\) and \(^{8}Be\), respectively). For the channel \(^{103}Rh(^{16}O, 2\alpha 2n)^{109}In\) the calculations overestimate the measured cross-sections as shown in Fig. 5.2.4(a). It is expected because the metastable states of half lives 1.3 \(m\) and 0.2 \(sec.\) of \(^{109}In\) could not be observed and the code calculates the total cross-section and not the contributions separately for the ground and metastable states.

In case of \(^{103}Rh(^{16}O, 3\alpha n)^{106m}Ag\) and \(^{103}Rh(^{16}O, 3\alpha 3n)^{104g}Ag\) reactions theoretical prediction of code PACE give negligible cross-sections while the measured cross-sections are substantial, as shown in Fig. 5.2.4(b) and (c). This discrepancy of higher experimentally measured cross-sections as compared to the theoretical calculations, may again be attributed to
Fig. 5.2.3 Excitation functions for the reactions $^{103}\text{Rh}^{(16O,pn)}^{117}\text{Te}$, $^{103}\text{Rh}^{(16O,p2n)}^{116}\text{Te}$, $^{103}\text{Rh}^{(16O,2p)}^{117}\text{Sb}$, $^{103}\text{Rh}^{(16O,2pn)}^{116m}\text{Sb}$, $^{103}\text{Rh}^{(16O,\alpha)}^{115}\text{Sb}$ and $^{101}\text{Rh}^{(16O,2\alpha)}^{111}\text{In}$. Theoretical calculations done with code PACE are represented by the solid lines.
Fig. 5.2.4 Excitation functions for the reactions $^{103}\text{Rh}(^{16}\text{O}, 2\alpha 2n)^{109}\text{In}$, $^{103}\text{Rh}(^{16}\text{O}, 3\alpha n)^{106m}\text{Ag}$ and $^{103}\text{Rh}(^{16}\text{O}, 3\alpha 3n)^{104}\text{Ag}$. Theoretical calculation done by code PACE is represented by the solid line.

the contributions coming from incomplete fusion of the $^{16}\text{O}$ ion. Since, theoretical calculations of PACE do not take into account the ICF, it may be inferred that a significant part of these reactions involving $\alpha$-emission channels go through ICF, at these energies.
System \((^{16}O + ^{130}Te)\)

The measured and calculated excitation functions for the reactions \(^{130}Te(^{16}O,5n)^{141}Nd\), \(^{130}Te(^{16}O,\alpha3n)^{139}Ce\), \(^{130}Te(^{16}O,3\alpha n)^{133}Xe\), \(^{130}Te(^{16}O,3\alpha n)^{135}Xe\) and \(^{130}Te(^{16}O,3\alpha3n)^{131m}Xe\) are shown in Fig 5.2.5. 

**Fig. 5.2.5** Excitation functions for the reactions \(^{130}Te(^{16}O,5n)^{141}Nd\), \(^{130}Te(^{16}O,\alpha3n)^{139}Ce\), \(^{130}Te(^{16}O,3\alpha n)^{133}Xe\), \(^{130}Te(^{16}O,3\alpha n)^{135}Xe\) and \(^{130}Te(^{16}O,3\alpha3n)^{131m}Xe\). The filled circles represent the experimental data. Various curves correspond to the theoretical predictions of the code PACE.
Calculations have been done using the code PACE with K=8, 9 and 10, respectively. It may be observed from the Fig 5.2.5(a) that a value of K=9 well reproduces the experimental data for the 5n channel, which is expected to be formed by CF only. Further, in case of reaction $^{130}\text{Te}(^{16}\text{O}, \alpha 3n)^{139}\text{Ce}$, the measured EF [Fig. 5.2.5(b)] exceeds the theoretical EF, which again indicates that ICF plays an important role. Moreover, for $^{130}\text{Te}(^{16}\text{O}, 3\alpha n)^{133}\text{mXe}$ and $^{130}\text{Te}(^{16}\text{O}, 3\alpha 3n)^{131}\text{mXe}$ channels the theoretical calculations of PACE show negligible cross-sections (and hence not shown in figures) while the measured cross-sections are appreciable. Thus, it may again be inferred that these channels may have significant contributions from the ICF processes, as shown in Figs. 5.2.5(c) and (d).

5.3 Analysis using code CASCADE

The code CASCADE[3] developed by F. Puhlhofer is based on Hauser-Feshbach theory[18] for evaporation calculations. This code computes the reaction cross-sections for the residues 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. 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, which are stored permanently on the disc. The optical model potentials of Becchetti and Greenlees[9] are used for calculating the transmission coefficients for pro-
tons and neutrons, and the optical model potential of Satchler[19] is used for \( \alpha \) particles. In this code for calculating binding energies, Myers-Swiatecki Lysekil[8] mass formula has been used. The Fermi-gas model is used in the code to calculate the level densities of the product nuclei. In the code CASCADE 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 \( F_\theta \) are the parameters, which may be varied to match the experimental data. 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.

Excitation functions calculated using the code CASCADE are shown in Figs. 5.3.1 to 5.3.3. It may be observed from these figures that the value of \( K=10 \) and \( F_\theta=0.85 \) are best suited for the present measurements. The precursor contributions in cases of reactions \(^{103}Rh(\^{16}O,pn)\), \(^{103}Rh(\^{16}O,p2n)\), \(^{103}Rh(\^{16}O,2p)\) and \(^{103}Rh(\^{16}O,2pn)\)[Fig. 5.3.1] have been separated using the standard formulation as mentioned earlier. Further in case of reaction \(^{103}Rh(\^{16}O,\alpha)\)[Fig.5.3.2(a)] the theoretical calculations have a lower value than the experimental data. It may be due to contribution of ICF channel. In case of \(^{103}Rh(\^{16}O,2\alpha)\) and \(^{103}Rh(\^{16}O,2\alpha2n)\)[Figs.5.3.2(b) and (c)] reactions the measured cross-sections lie below the theoretical values. It is expected because only the ground state cross-sections have been measured. The theoretical calculations, however give the total cross-sections for both the ground and metastable states. In case of reactions \(^{103}Rh(\^{16}O,3\alpha n)\) and
Fig. 5.3.1 Excitation functions for the reactions $^{103}Rh(^{16}O,pn)^{117}\text{Te}$, $^{103}Rh(^{16}O,p2n)^{116}\text{Te}$, $^{103}Rh(^{16}O,2p)^{117}\text{Sb}$, and $^{103}Rh(^{16}O,2pn)^{116,\text{m}}\text{Sb}$. Theoretical calculations done with code CASCADE are represented by the various lines.
Fig. 5.3.2 Excitation functions for the reactions $^{103}Rh(^{16}O,\alpha)^{115}Sb$, $^{103}Rh(^{16}O,2\alpha)^{119}In$ and $^{103}Rh(^{16}O,2\alpha2n)^{109}In$. Theoretical calculations done with code CASCADE are represented by the dotted and solid lines.
$^{103}\text{Rh}(^{16}\text{O}, 3\alpha 3n)$ theoretical calculations using code CASCADE give negligible value for cross-sections. However, as shown in Figs. 5.3.3(a) and (b) experimental values are $\approx 10^{-30}$ mb. In these two cases, it appears that the reactions predominantly proceed through ICF.

![Excitation functions for the reactions $^{103}\text{Rh}(^{16}\text{O}, 3\alpha 3n)^{106m}\text{Ag}$ and $^{103}\text{Rh}(^{16}\text{O}, 3\alpha 3n)^{104\alpha}\text{Ag}$.](image)

**Fig. 5.3.3** Excitation functions for the reactions $^{103}\text{Rh}(^{16}\text{O}, 3\alpha 3n)^{106m}\text{Ag}$ and $^{103}\text{Rh}(^{16}\text{O}, 3\alpha 3n)^{104\alpha}\text{Ag}$.

### 5.4 Analysis using SUMRULE model

As has already been mentioned, it is possible to calculate cross-sections for CF and ICF channels using the SUMRULE[20] model. The underlying assumption in the SUMRULE model is that the ICF channels open only for those partial waves which have $\ell$ values greater than $\ell_{\text{critical}} (\ell \geq \ell_{\text{critical}})$. On the other hand, partial waves of $\ell < \ell_{\text{critical}}$ values contribute to CF. There are
three important parameters in the model viz., the temperature $T$ of the contact zone, the diffuseness $\Delta$ of the $T_t$ distribution, and the Coulomb interaction radius $R_C$. The values $T=3.5\, \text{MeV}$, $\Delta=1.7\, \text{fm}$ and $R_C=12\, \text{fm}$ have been suggested[20] for these parameters. The reaction residues, the ground state $Q$-values $Q_{gg}$[17], experimental measured cross-sections and cross-sections calculated by SUMRULE model for ICF and CF channels populated in the system $^{16}O + ^{169}Tm$ at $\approx 81\, \text{MeV}$ incident beam energy are given in Table 5.4.1.

<table>
<thead>
<tr>
<th>Residue</th>
<th>$Q_{gg}$ (MeV)</th>
<th>$\sigma(\text{Experimental})$ (mb)</th>
<th>$\sigma(\text{SUMRULE})$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{171}\text{Lu}$</td>
<td>-11.2</td>
<td>69.6±15.0</td>
<td>1.5×10^{-2}</td>
</tr>
<tr>
<td>$^{172}\text{Lu}$</td>
<td>-12.5</td>
<td>32.2±4.2</td>
<td>1.0×10^{-2}</td>
</tr>
<tr>
<td>$^{175}\text{Hf}$</td>
<td>-23.5</td>
<td>193.9±40.1</td>
<td>4.2×10^{-3}</td>
</tr>
<tr>
<td>$^{171}\text{Hf}$</td>
<td>-34.1</td>
<td>12.9±3.9</td>
<td>2.0×10^{-4}</td>
</tr>
<tr>
<td>$^{181}\text{Re}$</td>
<td>-21.9</td>
<td>40.2±12.1</td>
<td>8.1</td>
</tr>
<tr>
<td>$^{183}\text{Os}$</td>
<td>-35.6</td>
<td>-</td>
<td>2.0</td>
</tr>
<tr>
<td>$^{182}\text{Os}$</td>
<td>-36.3</td>
<td>-</td>
<td>1.6</td>
</tr>
<tr>
<td>$^{181}\text{Os}$</td>
<td>-48.5</td>
<td>-</td>
<td>5.2×10^{-2}</td>
</tr>
<tr>
<td>$^{182}\text{Ir}$</td>
<td>-51.2</td>
<td>-</td>
<td>3.1×10^{-1}</td>
</tr>
<tr>
<td>Complete fusion channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{185}\text{Ir}$</td>
<td>-25.7</td>
<td>495±85</td>
<td>535</td>
</tr>
</tbody>
</table>
As may be seen from the table, the calculated and experimental cross-sections for CF channel agree reasonably well. However, there is a large discrepancy between the measured and calculated cross-section values for ICF channels. Similar discrepancy in case of $^{13}C + ^{181}Ta$ system studied by Babu et al.[21], in his experiments at $\approx 6$ $MeV/nucleon$ energy has also been observed. Wilczyński et al.[20], tested the SUMRULE model for reactions at 8-10 $MeV/nucleon$ energy and found satisfactory agreement in the calculated and experimental cross-sections. The possible reason for the disagreement between the experimental and SUMRULE model calculations for ICF channels in the present case, may be the non-validity of the concept of critical angular momentum at these low energies. The cluster structure of the incident ion may also play important role in ICF reactions.

5.5 Recoil range distributions

In order to separate out the relative contributions of complete and incomplete fusion, the recoil range distributions (RRDs) for some residues produced in the interaction of $^{16}O$ with $^{169}Tm$ have been measured at $\approx 76$ and $81$ $MeV$ incident energies. The measured differential RRDs for various evaporation residues are shown, respectively in Figs. 5.5.1 and 5.5.2. It may be pointed out that, in our earlier analysis of some excitation functions[22, 23], enhancement of cross-sections was observed for some of these channels.

The measured recoil range distributions for eight residues $^{182}Ir$, $^{182,181}Os$, $^{181}Re$, $^{175,171}Hf$ and $^{172,171}Lu$ at $\approx 76$ $MeV$ energy are shown in Figs. 5.5.1.(a)-(l). Similarly, the measured data for the recoil ranges of nine
Fig. 5.5.1 Measured recoil range distributions of evaporated residues at \( \approx 76 \text{ MeV} \) energy, in the system \(^{16}O + ^{169}Tm\).
Fig. 5.5.2 Measured recoil range distributions of evaporated residues at \( \approx 81 \) MeV energy, in the system \( ^{16}O + ^{169}Tm \).
residues $^{182}Ir$, $^{183g,182,181g}Os$, $^{181}Re$, $^{175,171}Hf$ and $^{172g,171g}Lu$ at $\approx81$ MeV incident energy have been plotted in Figs. 5.5.2.(a)-(i). An attempt has been made to fit experimentally observed recoil ranges of residues by Gaussian peaks using the software ORIGIN. The Gaussian fit for recoil ranges in case of $^{182}Ir$, and $^{182,181g}Os$ at $\approx76 MeV$ and for the residues $^{182}Ir$ and $^{183g,182,181g}Os$ at $\approx81 MeV$ show only one peak. However, the experimental RRD data for the residues $^{181}Re$, $^{175,171}Hf$ and $^{172g,171g}Lu$ at $\approx76 MeV$ and for the residues $^{181}Re$, $^{175,171}Hf$ and $^{172g,171g}Lu$ at $\approx81 MeV$ may be fitted by more than one peaks. Each case is discussed individually in the following;

1. RRD for the residue $^{182}Ir$

As has already been said this residue is produced from the reaction $^{169}Tm(^{16}O,3n)$. The experimental data for the recoil range distributions both at $\approx76$ and $81 MeV$ energies can be well fitted by Gaussian distributions with peaks at cumulative thickness $\approx276$ and $370 \mu g/cm^2$, respectively [Figs. 5.5.3.(a) and (b)]. The recoil range for the residue has also been calculated using stopping power tables of Northcliffe and Schilling[24]. The calculated values agree well with the measured data. It may, therefore, be inferred that the residue $^{182}Ir$ is produced only by the complete fusion process.

2. RRD for the residue $^{183g}Os$

The experimentally measured recoil range data with the Gaussian fit for this residue at $\approx81 MeV$ has been plotted in Fig. 5.5.4. The observed RRD for the residue $^{183g}Os$ may be fitted by one Gaussian peak at the cumulative thickness $\approx370 \mu g/cm^2$. The calculations of the recoil range for this
Fig. 5.5.3 Gaussian fits to the measured recoil range data for the residue $^{182}$Ir at 76 and 81 MeV energies.
residue has been performed using reference[24], which agree with the measured value. This residue may, therefore, be formed by the complete fusion of $^{16}O$ with the target nucleus $^{169}Tm$, through the reaction $^{169}Tm(^{16}O,pn)$.

![Graph showing Gaussian fit to measured recoil range data for the residue $^{183}Os$ at 81 MeV energy.](image)

**Fig. 5.5.4** Gaussian fit to the measured recoil range data for the residue $^{183}Os$ at 81 MeV energy.

### 3. RRD for the residue $^{182}Os$

The Gaussian fits of the RRD data for the residue $^{182}Os$ at $\approx 76$ & 81 MeV energies are shown in Figs. 5.5.5(a) and (b). As may be observed, the experimental RRD data at both the incident energies may be fitted by a single peak, at $\approx 276 \ \mu g/cm^2$ for $\approx 76$ MeV energy and $\approx 370 \ \mu g/cm^2$ thickness for $\approx 81$ MeV. Since, only one peak appears at each incident energy, it may be concluded that the residue $^{182}Os$ is populated only by complete fusion at both the incident energies through the reaction $^{169}Tm(^{16}O,p2n)$. 

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Fig. 5.5.5 Gaussian fits to the measured recoil range data for the residue $^{182}\text{Os}$ at 76 and 81 $\text{MeV}$ energies.
Further, the experimental value of the absorber thickness at peak position agrees well with the calculations done using stopping power values.

4. RRD for the residue $^{181}$Os

The measured RRD data for the residue $^{181}$Os both at $\approx76$ & $81$ MeV incident energies may be fitted by a single peak, at $\approx276 \mu g/cm^2$ thickness for $\approx76$ MeV and at $\approx370 \mu g/cm^2$ thickness for $\approx81$ MeV [Figs. 5.5.6(a) and (b)]. These peaks may be well understood, if it is assumed that the residue is produced by complete fusion in the reaction $^{169}Tm(^{16}O,p3n)$. The observed cumulative thicknesses of $\approx276$ & $370 \mu g/cm^2$ are well reproduced by theoretical calculations also.

5. RRD for the residue $^{181}$Re

The recoil range distributions for the residue $^{181}$Re at both the incident energies ($\approx76$ & $81$ MeV) are shown in Figs. 5.5.7(a) and (b). As may be observed from the figures the measured RRD data for this residue can be fitted by more than one Gaussian peaks. At the incident energy $\approx76$ MeV, the RRD data may be resolved into two Gaussian peaks one at $\approx221 \mu g/cm^2$ and the other at $\approx348 \mu g/cm^2$ thickness. The Gaussian peaks for the $\approx81$ MeV data appear at the cumulative thicknesses $\approx265$ and $380 \mu g/cm^2$, respectively. The peaks at higher cumulative thicknesses ($\approx348 \mu g/cm^2$ at $\approx76$ MeV and $\approx380 \mu g/cm^2$ at $81$ MeV) correspond to the residue which are populated by CF of $^{16}O$ with the target on the other hand peaks at thicknesses $\approx221 \mu g/cm^2$ at 76 MeV and $\approx265 \mu g/cm^2$ at 81 MeV may be assigned to those residues which are produced by ICF of $^{16}O$. 

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Fig. 5.5.6 Gaussian fits to the measured recoil range data for the residue $^{181}$Os at 76 and 81 MeV energies.
Fig. 5.5.7 Gaussian fits to the measured recoil range data for the residue $^{181}$Re at 76 and 81 MeV energies.
Hence, it may be concluded that the residues produced by $^{169}\text{Tm}(^{16}O,\alpha)$ channel may have contributions of complete as well as incomplete fusion. The relative contributions of the complete and incomplete fusion channels may be obtained from the intensity of the corresponding Gaussian peaks. The percentage contributions for the complete fusion and incomplete fusion channels are presented in Table 5.5.1.

6. RRD for the residue $^{175}\text{Hf}$

In Figs. 5.5.8(a) and (b), the recoil range data for the residue $^{175}\text{Hf}$ have been plotted. The RRD data for this residue can be fitted by three Gaussian peaks, at both the incident energies $\approx 76$ and $81\ MeV$. The Gaussian peaks are observed at $\approx 110$, $185$ and $295\ \mu g/cm^2$ thicknesses, respectively for the energy $\approx 76\ MeV$. In case of $\approx 81\ MeV$ incident beam energy, the peaks are observed at the thickness $\approx 130$, $300$ and $396\ \mu g/cm^2$, respectively. The inspection of these figures indicates that at $\approx 76\ MeV$ incident energy, the residue $^{175}\text{Hf}$ formed by the incomplete fusion of $^{16}O$ (fusion of $^{8}Be$) is stopped in the absorber thickness within the range of $\approx 110\ \mu g/cm^2$, While the same residue formed by the incomplete fusion of $^{16}O$ (fusion of $^{12}C$) has a range of $\approx 185\mu g/cm^2$. At the higher incident energy of $\approx 81\ MeV$, the corresponding ranges are $\approx 130$ and $300,\ \mu g/cm^2$. The peak appearing at the highest absorber thicknesses of $\approx 295\ \mu g/cm^2$ at $\approx 76\ MeV$ and $\approx 396\ \mu g/cm^2$ at $\approx 81\ MeV$ incident energy are due to the complete fusion of $^{16}O$. The theoretical calculations for these recoil ranges performed using the reference[24] satisfactorily reproduced the measured values.
Fig. 5.5.8 Gaussian fits to the measured recoil range data for the residue $^{175}\text{Hf}$ at 76 and 81 MeV energies.
7. RRD for the residue $^{171}Hf$

The Gaussian fits of the measured recoil range data for the residue $^{171}Hf$ have been plotted in the Figs. 5.5.9(a) and (b). The RRD data for this residue can be fitted by three Gaussian peaks at \( \approx 110 \), 170 and 289 \( \mu g/cm^2 \) thickness for \( \approx 76 \) MeV incident energy and two peaks at \( \approx 282 \) and 390 \( \mu g/cm^2 \) cumulative thickness for \( \approx 81 \) MeV. The three peaks for the data at \( \approx 76 \) MeV may be assigned respectively, to the ICF of $^{16}O$ (the peak at \( \approx 110 \mu g/cm^2 \) to the fusion of $^{8}Be$, the peak at \( \approx 170 \mu g/cm^2 \) to the fusion of $^{12}C$) and CF of $^{16}O$ (\( \approx 289 \mu g/cm^2 \)). In a similar way, the peaks at \( \approx 81 \) MeV incident energy may be attributed to the ICF of $^{16}O$ (the peak at \( \approx 282 \mu g/cm^2 \) thickness to the fusion of $^{12}C$) and of CF of $^{16}O$ (the peak at \( \approx 390 \mu g/cm^2 \)). At \( \approx 81 \) MeV incident energy the peak due to the ICF of $^{16}O$ (corresponding to the fusion of $^{8}Be$) has not been observed.

8. RRD for the residue $^{172g}Lu$

The measured RRD data for the residue $^{172g}Lu$ can be fitted by two Gaussian peaks at both the incident energies \( \approx 76 \) and \( \approx 81 \) MeV [Figs. 5.5.10(a) and (b)]. At the incident energy \( \approx 76 \) MeV, the RRD data can be fitted at the cumulative thicknesses \( \approx 105 \) and 175 \( \mu g/cm^2 \) while at the incident energy \( \approx 81 \) MeV the data can be fitted by Gaussian peaks at \( \approx 120 \) and 276 \( \mu g/cm^2 \) thickness. From Figs. 5.5.10(a) and (b) it may be observed that peaks at the cumulative thicknesses \( \approx 105 \) and 120 \( \mu g/cm^2 \) correspond to the residue formed via ICF of $^{16}O$ (fusion of $^{8}Be$). The peaks observed at the cumulative thicknesses \( \approx 175 \) and 276 \( \mu g/cm^2 \) correspond to the residue
Fig. 5.5.9 Gaussian fits to the measured recoil range data for the residue $^{171}\text{Hf}$ at 76 and 81 MeV energies.
Fig. 5.5.10 Gaussian fits to the measured recoil range data for the residue $^{172}$Lu at 76 and 81 MeV energies.
formed in the reaction $^{169}Tm(^{16}O, 3\alpha)$ through ICF of $^{16}O$ (fusion of $^{12}C$).

It is interesting to note that in this case no peak has been observed for the CF of $^{16}O$ with the $^{169}Tm$ at both the incident energies.

9. RRD for the residue $^{171}gLu$

The experimentally measured RRD data for the residue $^{171}gLu$, at both the incident beam energies $\approx 76$ and $81\ MeV$ has been plotted in Figs. 5.5.11(a) and (b). As may be seen from these figures, the RRD data can be fitted by three Gaussian peaks at both the incident energies. At energy $\approx 76\ MeV$, the Gaussian peaks appear at the thicknesses of $\approx 44$, 154 and 197 $\mu g/cm^2$, while for the $\approx 81\ MeV$ incident energy, peaks appear at thicknesses of $\approx 60$, 175 and 330 $\mu g/cm^2$. The peaks at lowest cumulative thicknesses $\approx 44\ \mu g/cm^2$ for $\approx 76\ MeV$ and $\approx 60\ \mu g/cm^2$ for $\approx 81\ MeV$, may be assigned to the ICF of $^{16}O$ (fusion of $^{4}He$). The peaks at larger cumulative thicknesses may be assigned respectively to the ICF of $^{16}O$ (fusion of $^{8}Be$ and $^{12}C$). It may be observed that again no peak appears for the complete fusion of $^{16}O$ with the target nucleus. In general, the observed positions of peaks in measured RRD data agree with the theoretical calculations of ranges made using stopping power values taken from tables of Northcliffe and Schilling[24].

In order to separate out the relative contributions of complete and incomplete fusion in $\alpha$-emission channels, the areas under the peaks in Figs. 5.5.7 to 5.5.11 have been computed. The relative contributions of the processes are obtained by dividing the intensity of the corresponding peak (complete fusion/incomplete fusion) by the total area and are given in Table 5.5.1.
Fig. 5.5.11 Gaussian fits to the measured recoil range data for the residue $^{171}\text{Lu}$ at 76 and 81 $MeV$ energies.
Table 5.5.1 Energy dependence of relative contributions of CF and ICF at ≈76, 81 and 86 MeV (The RRD data at 86 MeV are taken from one of our earlier work[22]).

<table>
<thead>
<tr>
<th>Reaction-Residue</th>
<th>$E_{lab}$ (MeV)</th>
<th>CF</th>
<th>ICF of $^{12}$C</th>
<th>ICF of $^{8}$Be</th>
<th>ICF of α</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $^{169}$Tm($^{16}$O, α)$^{181}$Re</td>
<td>75.5±0.5</td>
<td>85%</td>
<td>15%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>80.5±0.4</td>
<td>80%</td>
<td>20%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$^{185.9}±0.5$</td>
<td>35%</td>
<td>65%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2. $^{169}$Tm($^{16}$O, 2αpn)$^{175}$Hf</td>
<td>75.5±0.5</td>
<td>27%</td>
<td>16%</td>
<td>57%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>80.5±0.4</td>
<td>26%</td>
<td>40%</td>
<td>34%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$^{185.9}±0.5$</td>
<td>25%</td>
<td>46%</td>
<td>29%</td>
<td>-</td>
</tr>
<tr>
<td>3. $^{169}$Tm($^{16}$O, 2α5n)$^{171}$Hf</td>
<td>75.5±0.5</td>
<td>64%</td>
<td>15%</td>
<td>21%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>80.5±0.4</td>
<td>35%</td>
<td>65%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>4. $^{169}$Tm($^{16}$O, 3αn)$^{172}$Lu</td>
<td>75.5±0.5</td>
<td>-</td>
<td>45%</td>
<td>55%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>80.5±0.4</td>
<td>-</td>
<td>32%</td>
<td>68%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$^{185.9}±0.5$</td>
<td>-</td>
<td>-</td>
<td>80%</td>
<td>20%</td>
</tr>
<tr>
<td>5. $^{169}$Tm($^{16}$O, 3α2n)$^{171}$Lu</td>
<td>75.5±0.5</td>
<td>-</td>
<td>61%</td>
<td>14%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>80.5±0.4</td>
<td>-</td>
<td>53%</td>
<td>23%</td>
<td>24%</td>
</tr>
<tr>
<td></td>
<td>$^{185.9}±0.5$</td>
<td>-</td>
<td>-</td>
<td>26%</td>
<td>74%</td>
</tr>
</tbody>
</table>


The over all errors in relative contributions are expected to be less than ≈20%. The plots of relative contribution verses incident energy are shown in Figs. 5.5.12 to 5.5.15. The continuous and dotted lines in the above figures are just to guide the eye. In case of the residue $^{181}$Re [Fig. 5.5.12], it may be
observed that the relative contribution of CF of $^{16}O$ decreases, while the contribution of ICF of $^{16}O$ (fusion of $^{12}C$) increases with the increase of incident energy. As shown in Fig. 5.5.13 for the reaction $^{169}Tm(^{16}O,2\alpha \alpha n)^{175}Hf$, the relative contribution for the CF of $^{16}O$ decreases and the contributions of ICF of $^{16}O$ (fusion of $^{12}C$ and $^8Be$) increase as a function of incident energy. The relative contributions for the residue $^{172}Lu$ (from the reaction $^{169}Tm(^{16}O,3\alpha \alpha n)$) are shown in Fig. 5.5.14. It may be observed that the contribution of ICF of $^{16}O$ (fusion of $^{12}C$) increases and the contribution of ICF of $^{16}O$ (fusion of $^8Be$) decreases almost linearly with the beam energy. For the residue $^{173}Lu$, plots of the relative contributions of CF and ICF as a function of beam energy are given in Fig. 5.5.15. Again, the contribution for the ICF of $^{16}O$ (fusion of $^{12}C$) is found to decrease and the contribution for ICF of $^{16}O$ (fusion of $^8Be$ and $^4He$) is found to increase with the beam energy.
Fig. 5.5.13 Relative contributions of complete and incomplete fusion as a function of beam energy for the residue $^{175}\text{Hf}$

Fig. 5.5.14 Relative contributions of complete and incomplete fusion as a function of beam energy for the residue $^{172}\text{Lu}$
Fig. 5.5.15 Relative contributions of complete and incomplete fusion as a function of beam energy for the residue $^{171}\text{Lu}$

5.6 Angular distributions of evaporation residues at $\approx 81\,\text{MeV}$

In the present work, the angular distributions for the six residues formed in the reactions $^{169}\text{Tm}(^{16}\text{O},3\gamma n)^{182}\text{Ir}$, $^{169}\text{Tm}(^{16}\text{O},4\alpha n)^{181}\text{Ir}$, $^{169}\text{Tm}(^{16}\text{O},p2\gamma n)^{182}\text{Os}$, $^{169}\text{Tm}(^{16}\text{O},p3\gamma n)^{181}\text{Os}$, $^{169}\text{Tm}(^{16}\text{O},\alpha)^{181}\text{Re}$ and $^{169}\text{Tm}(^{16}\text{O},3\alpha n)^{172}\text{Lu}$ have been measured at $\approx 81\,\text{MeV}$ incident energy. The measured angular distributions for the above residues are presented in Figs. 5.6.1 to 5.6.6. As may be observed in Figs. 5.6.1 to 5.6.4 the residues $^{182}\text{Ir}$, $^{181}\text{Ir}$, $^{182}\text{Os}$ and $^{181}\text{Os}$ are mostly emitted within the forward cone of half angle $30^\circ$ from the beam direction. Further, the peak of the distribution lies between $0^\circ - 13^\circ$ range. This is expected if the above mentioned residues are produced by complete fusion. Theoretical calculations done using code
PACE, which takes into account only complete fusion, indicates the emission of residues peaking at \( \approx 3^\circ \) to \( 4^\circ \) from the beam direction and extending up to \( \approx 18^\circ \). The experimental angular distributions for residues \(^{181}\)Re and \(^{172g}\)Lu are shown in Figs. 5.6.5 & 5.6.6. In case of \(^{181}\)Re, two peaks may be observed one within around \( 0^\circ - 13^\circ \), which may be assigned to the residues populated by complete fusion and the other in the angular range \( 45^\circ - 60^\circ \). The second peak may be assigned to the residues populated by incomplete fusion. The observed angular distribution of the residue \(^{172g}\)Lu is shown in Fig. 5.6.6. As may be seen from the figure, the distribution show no data up to \( 30^\circ \), and a peak is observed in the angular range \( 39^\circ \) to \( 64^\circ \). This clearly indicates that the residue \(^{172g}\)Lu is populated mostly by incomplete fusion.

**Fig. 5.6.1** Angular distribution of residue \(^{182}\)Ir at \( \approx 81 \) MeV incident energy.
**Fig. 5.6.2** Angular distribution of residue $^{181}$Ir at $\approx$81 $MeV$ incident energy.

**Fig. 5.6.3** Angular distribution of residue $^{182}$Os at $\approx$81 $MeV$ incident energy.
Fig. 5.6.4 Angular distribution of residue $^{181}$Os at $\approx 81 \text{ MeV}$ incident energy.

Fig. 5.6.5 Angular distribution of residue $^{181}$Re at $\approx 81 \text{ MeV}$ incident energy.
**Fig. 5.6.6** Angular distribution of residue $^{172g}$Lu at $\approx 81$ MeV incident energy.

**Conclusions**

The present experiments have been designed to study mechanism of heavy ion induced reactions. In particular, an attempt has been made to study the complete and incomplete fusion of $^{14}N$ with $^{128}Te$ and $^{16}O$ with $^{130}Te$, $^{103}Rh$ and $^{169}Tm$ targets. Three types of measurements have been done. The excitation functions for various channels leading to radioactive residues have been measured, and are compared with the theoretical calculations done using available computer codes viz., ALICE-91, PACE and CASCADE. It may be pointed out that all the above mentioned codes take into account only the complete fusion process. It has been observed that for some reaction channels the experimentally measured cross-sections are order of magnitude larger than the calculated ones, indicating the presence of incomplete fusion.
Calculations for cross-sections have also been performed using SUMRULE model. This model calculates both the complete and the incomplete fusion cross-sections. The cross-sections for incomplete fusion channels calculated with SUMRULE model are very much smaller than the measured values. However, the cross-sections for complete fusion are in agreement with the experimental data. The large discrepancy for ICF channels may be due to the cluster structure of the projectile and/or due to the non-validity of the concept of critical angular momentum.

In order to find out the relative contributions of the complete and incomplete fusion channels, recoil range distributions for some residues have been measured. Analysis of the data, in some cases has shown additional peaks in the recoil range distributions at catcher thicknesses smaller than the expected range of the residue due to complete fusion. Since, only a part of the incident energy is imparted to the recoiling residue in case of incomplete fusion, the peaks at smaller catcher thicknesses may be assigned to the incomplete fusion channels. The recoil range data has been fitted with Gaussian peaks. The relative contributions of complete fusion and incomplete fusion channels have been estimated from the ratio of the area under a given peak to the total area. In some cases $^{169}Tm(^{16}O, 3αn)$ and $^{169}Tm(^{16}O, 3α2n)$ no peak in the recoil range distributions could be assigned to the complete fusion and therefore, the residues $^{172}Lu$ and $^{171}Lu$ are assumed to be populated only by incomplete fusion.

In case of complete fusion the reaction residues are emitted in a cone of small angle along the beam direction. However, in case of incomplete fusion
the recoiling residues are expected to emerge at larger angles with respect to the beam direction. As such, angular distributions of the residues with respect to the beam direction also provide complementary information about the complete and incomplete fusion. In the present experiment, angular distributions of some residues for the system $^{16}O + ^{169}Tm$ have been measured. The analysis of the angular distribution data further confirms the presence of incomplete fusion. The relative contributions of complete and incomplete fusion have been separated for the channel $^{169}Tm(^{16}O, \alpha)^{211}Re$ from both the recoil range and angular distribution measurements. The recoil range measurements give $\approx 80\%$ contribution for complete fusion and $\approx 20\%$ contribution for incomplete fusion of $^{16}O$ (at 81 MeV incident energy), while the angular distribution measurements give $\approx 82\%$ and $\approx 18\%$ contribution for the same complete and incomplete fusion. As such there is satisfactory agreement in the two measurements. The data of present measurement may be of use in developing a model for incomplete fusion.
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10. Incomplete fusion studies using particle-gamma coincidence technique:; Pushpendra. P. Singh, Bhavna Sharma, **Unnati**, Manoj K. Sharma, B.


10. Incomplete fusion studies using particle-gamma coincidence technique; Pushpendra. P. Singh, Bhavna Sharma, Unnati, Manoj K. Sharma, B.


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NSC reports


Complete and incomplete fusion reactions in the $^{16}$O+$^{169}$Tm system: Excitation functions and recoil range distributions

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With the view to study complete and incomplete fusion in heavy ion induced reactions, experiments have been carried out for measuring excitation functions for several reactions in the system $^{16}$O+$^{169}$Tm at energies near the Coulomb barrier to well above it, using an activation technique. The measured excitation functions have been compared with those calculated theoretically using three different computer codes viz., ALICE-91, CASCADE and PACE2. The enhancement of experimentally measured cross sections for alpha emission channels over their theoretical prediction has been attributed to the fact that these residues are formed not only by complete fusion but also through incomplete fusion. In order to separate out the relative contributions of complete and incomplete fusion, the recoil range distributions of eight residues produced in the interaction of $^{16}$O with $^{169}$Tm at $\approx$87 MeV have been measured. The recoil range distributions indicate significant contributions from incomplete fusion at $\approx$87 MeV for some of the channels.

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I. INTRODUCTION

During the last couple of years there has been a renewed interest in the study of incomplete fusion reactions in heavy ion (HI) interactions particularly with heavier target nuclei. It has been observed that at energies just above the Coulomb barrier, both the complete fusion (CF) and the incomplete fusion (ICF) may be the dominant reaction mechanisms. In CF reactions, the incident ion completely fuses with the target nucleus, forming an excited composite system, from which particles and/or $\gamma$-rays may be emitted. However, in case of ICF, the projectile is assumed to break up into the fragments (e.g., $^{16}$O may break up into $^{12}$C and an $\alpha$-particle; two $^6$Be fragments; an $\alpha$-particle and $^{12}$C), one of which fuses with the target nucleus while the rest of it moves in the forward direction with almost same velocity as that of incident ion. The excited system formed as a result of the fusion of one of the fragments of the incident ion may also undergo de-excitation by the emission of particles and/or gamma rays. Recent measurements of excitation functions (EFs) [1–4] for the production of large number of residues in HI reactions have indicated that ICF plays an important role in such reactions. However, the relative contributions of CF and ICF components, their dependence on energy, projectile-target combinations, etc. have not yet been fully explored and understood. Such measurements are still limited to a few systems only. As such, to have a better understanding of CF and ICF processes, more experimental data on EFs and recoil range distributions (RRDs) of the residues in HI reactions, covering a wide range of the periodic table and energy is required. It is possible to separate out the relative contributions of various ICF channels at energies near and just above the Coulomb barrier from the measurement of EFs and the RRD of evaporation residues. The measurement of RRD is based on the linear momentum transfer of the projectile to the target nucleus. In CF reactions, the linear momentum is completely transferred to the target nucleus, while in the case of ICF reactions, partial transfer of projectile momentum takes place. Most of the earlier studies of ICF reactions have been done at beam energies $\geq$10 MeV/nucleon using medium-mass targets. However, there are limited studies at lower beam energies with heavier targets ($A \geq 150$). Further, when medium mass targets are used, it becomes difficult to distinguish the residues produced by CF and ICF mechanisms, as $\alpha$-emission from the fused excited system is quite pronounced. However, if heavier targets are used, the emission of $\alpha$-particles from the fused excited system is likely to be substantially reduced [5] due to the high Coulomb barrier. As a result, the emission of $\alpha$-particles in ICF channels will give rise to heavy residues which have a very little contribution from CF channels. With a view to study CF and ICF in several projectile-target combinations, a program of precise measurement and analysis of EFs and RRD has been undertaken [6–10]. In the present work, excitation functions for eight reactions in the system $^{16}$O+$^{169}$Tm, in the energy range $\approx$71–95 MeV and recoil range distributions of the residues in the Al-catcher foils at $\approx$87 MeV beam energy have been measured, using the activation technique. The measured EFs have been compared with theoretical calculations done using three different codes viz., ALICE-91 [11], CASCADE [12], and PACE2 [13]. To the best of our knowledge these EFs as well as the RRDs have been measured for the first time. The analysis of EFs and RRDs have clearly indicated that ICF is a dominant mode of reaction mechanism at these energies. The experimental details are discussed in Sec. II of the paper. The analysis of excitation functions and recoil range distribution are given in Secs. III and IV of the paper, respectively.
II. EXPERIMENTAL DETAILS

Excitation functions

The experiments have been carried out using the 15 UD Pelletron accelerator facility of the Nuclear Science Center (NSC), New Delhi, India. Details of sample preparation, irradiation, post-irradiation analysis, etc., are given in the following sections.

1. Sample preparation

The samples of natural $^{169}$Tm were prepared by the vacuum evaporation technique. The thickness of each target was determined by the $\alpha$ transmission method which is based on the measurement of the energy lost by 5.485 MeV $\alpha$ particles obtained from an $^{241}$Am source, while passing through the sample. The thicknesses of the $^{169}$Tm deposited on Al foils ($\approx$ 1.5 mg/cm$^2$) were $\approx$0.6 mg/cm$^2$. The samples were cut into size of 1.2 $\times$ 1.2 cm$^2$ each and were pasted on rectangular Al-holders having concentric holes of 1.0 cm diameter. The Al-holders were used for rapid heat dissipation. The thick Al-backing of $^{169}$Tm samples served both as an energy degrader as well as a catcher, so that recoiling residues may be trapped in catcher thickness.

2. Irradiation

The irradiations were carried out in the General Purpose Scattering Chamber (GPSC) of 1.5 m diameter having an in-vacuum transfer facility at the Peiletron accelerator facility of NSC, New Delhi, India. Two stacks containing four $^{169}$Tm samples each were irradiated by an $^{16}$O$^+$ beam at $\approx$92 and $\approx$95 MeV, respectively. The beam current was $\approx$30–50 nA. The targets of $^{169}$Tm backed by an 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. Keeping in view the half lives of interest, the irradiations were carried out for $\approx$8 hours duration each. The delay time between the stop of irradiation and the beginning of counting was minimized using an in-vacuum transfer of samples. The total charge collected in the Faraday cup has been used to calculate the flux of the beam.

3. Post-irradiation analysis

The stack of samples after irradiation was taken out from the scattering chamber using an in-vacuum transfer facility. The activities induced in various samples were recorded by counting the target and catcher foils together using a HPGe $\gamma$-ray spectrometer coupled to the PC based multichannel analyzer. Software FREEDOM [14] has been used for recording and analysis of the data. The HPGe detector (resolution $\approx$2 keV for a 1.33 MeV $\gamma$-ray of $^{60}$Co) was precalibrated both for energy and efficiency using various standard $\gamma$ sources like $^{22}$Na, $^{54}$Mn, $^{57}$Co, $^{133}$Ba, $^{137}$Cs, and $^{152}$Eu. The geometry dependent efficiency of the HPGe detector for various source-detector distances was determined using a $^{152}$Eu source. A typical $\gamma$-ray spectrum of an irradiated $^{169}$Tm sample at 92 MeV is shown in Fig. 1. The various peaks in observed $\gamma$-ray spectra were assigned to different residues on the basis of their characteristic energy and measured half-lives. The data for the half-life was fitted using the software ORIGIN. A list of reactions, energy of identified $\gamma$-rays and their branching ratios are given in Table I. The intensities of the characteristic $\gamma$-rays were used to compute the reaction cross sections using the formulation [9]

$$
\sigma(E) = \frac{A\lambda \exp(\lambda \tau_2)}{N_0 \phi \theta K(Ge)[1 - \exp(-\lambda \tau_1)][1 - \exp(-\lambda \tau_2)]},
$$

where $A$ is the observed counts during the accumulation time $\tau_1$ of the induced activity of decay constant $\lambda$, $N_0$ is the number of target nuclei irradiated for time $\tau_1$ with a particle beam of flux $\phi$, $\tau_2$ is the time lapse between the stop of irradiation and the start of counting, $\theta$ is the branching ratio of the characteristic $\gamma$ ray and $Ge$ is the geometry dependent

<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>$^{169}$Tm($^{16}$O,3$n$)$^{182}$Ir</td>
<td>126.9</td>
<td>34.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>273.1,764.2</td>
<td>43.5,6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>891.1,912.2</td>
<td>5.7,8.7</td>
</tr>
<tr>
<td>2.</td>
<td>$^{169}$Tm($^{16}$O,4$n$)$^{181}$Ir</td>
<td>107.6,123.5</td>
<td>15.2,4.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>184.6,227.0</td>
<td>4.3,8.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>231.6,318.9</td>
<td>4.6,7.0</td>
</tr>
<tr>
<td>3.</td>
<td>$^{169}$Tm($^{16}$O,2$p$2$n$)$^{182}$Os</td>
<td>180.22</td>
<td>34.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>263.29</td>
<td>6.6</td>
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<tr>
<td>4.</td>
<td>$^{169}$Tm($^{16}$O,3$p$)$^{182}$Os</td>
<td>238.68</td>
<td>44</td>
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<td></td>
<td>826.74</td>
<td>20.2</td>
</tr>
<tr>
<td>5.</td>
<td>$^{169}$Tm($^{16}$O,2$p$2$n$)$^{181}$Re</td>
<td>360.7</td>
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<td></td>
<td></td>
<td>365.59</td>
<td>57.0</td>
</tr>
<tr>
<td>6.</td>
<td>$^{169}$Tm($^{16}$O,3$n$)$^{178}$Re</td>
<td>237.19</td>
<td>45</td>
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<tr>
<td>7.</td>
<td>$^{169}$Tm($^{16}$O,2$\alpha n$)$^{175}$Hf</td>
<td>343.4</td>
<td>87</td>
</tr>
<tr>
<td>8.</td>
<td>$^{169}$Tm($^{16}$O,3$\alpha n$)$^{172}$Lu</td>
<td>1093.6</td>
<td>63.5</td>
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</tbody>
</table>
TABLE II. The experimentally measured cross sections.

<table>
<thead>
<tr>
<th>Lab energy (MeV)</th>
<th>(\sigma^{(182}\text{Ir})) (mb)</th>
<th>(\sigma^{(181}\text{Ir})) (mb)</th>
<th>(\sigma^{(182}\text{Os})) (mb)</th>
<th>(\sigma^{(183}\text{Os})) (mb)</th>
<th>(\sigma^{(181}\text{Re})) (mb)</th>
<th>(\sigma^{(183}\text{Re})) (mb)</th>
<th>(\sigma^{(182}\text{Hf})) (mb)</th>
<th>(\sigma^{(172}\text{Lu})) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.7±1.0</td>
<td>3.28±0.7</td>
<td>—</td>
<td>4.58±1.4</td>
<td>1.26±0.6</td>
<td>2.72±0.4</td>
<td>2.66±0.7</td>
<td>—</td>
<td>—</td>
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<tr>
<td>74.9±0.9</td>
<td>42.30±7.1</td>
<td>28.47±12.5</td>
<td>82.77±10.0</td>
<td>39.98±5.1</td>
<td>4.81±1.2</td>
<td>5.35±0.7</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>78.7±0.9</td>
<td>59.86±13.9</td>
<td>110.00±15.65</td>
<td>139.41±22.9</td>
<td>78.85±13.8</td>
<td>32.81±4.3</td>
<td>137.37±28.7</td>
<td>1.74±0.2</td>
<td>14.93±2.1</td>
</tr>
<tr>
<td>82.0±0.8</td>
<td>86.43±14.8</td>
<td>170.47±28.4</td>
<td>155.6±20.7</td>
<td>68.15±8.3</td>
<td>129.0±16.3</td>
<td>391.49±83.0</td>
<td>5.2±0.8</td>
<td>20.58±2.6</td>
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<tr>
<td>85.8±0.8</td>
<td>47.64±7.7</td>
<td>250.16±67.7</td>
<td>107.46±14.4</td>
<td>59.28±7.5</td>
<td>198.02±23.3</td>
<td>594.02±90.6</td>
<td>9.02±1.2</td>
<td>0.57±0.1</td>
</tr>
<tr>
<td>88.9±1.0</td>
<td>35.23±3.9</td>
<td>316.79±34.8</td>
<td>71.50±9.9</td>
<td>35.84±6.2</td>
<td>250.92±31.1</td>
<td>607.94±86.7</td>
<td>27.34±5.3</td>
<td>2.53±0.4</td>
</tr>
<tr>
<td>91.6±0.4</td>
<td>13.77±3.2</td>
<td>229.84±39.6</td>
<td>29.37±4.1</td>
<td>15.45±4.4</td>
<td>153.8±17.8</td>
<td>526.23±78.6</td>
<td>32.14±3.7</td>
<td>2.96±0.5</td>
</tr>
<tr>
<td>94.6±0.4</td>
<td>8.47±1.4</td>
<td>183.89±27.2</td>
<td>18.42±3.7</td>
<td>9.85±2.7</td>
<td>173.1±22.8</td>
<td>441.99±66.9</td>
<td>34.31±5.5</td>
<td>4.62±0.6</td>
</tr>
</tbody>
</table>

Efficiency of the detector. The factor \([1-\exp(-\lambda t)]\) 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 \(\exp(\lambda t)\) and \([1-\exp(-\lambda t)]\), respectively. \(K = [1-\exp(-\mu/d)] \mu/d\) is the correction for the self absorption of the ray radiations in the sample thickness itself, where \(\mu\) is the thickness of the sample and \(\mu\) is the \(\gamma\) ray absorption coefficient.

Excitation functions for reactions \(^{169}\text{Tm(}^{160}\text{O,3n)}^{182}\text{Ir}, \(^{169}\text{Tm(}^{160,4n})^{181}\text{Ir}, \(^{169}\text{Tm(}^{160,2p2n})^{182}\text{Os}, \(^{169}\text{Tm(}^{160,3p3n})^{181}\text{Os}, \(^{169}\text{Tm(}^{160,2p2n})^{181}\text{Re}, \(^{169}\text{Tm(}^{160,2p2n})^{178}\text{Re}, \(^{169}\text{Tm(}^{160,2p2n})^{178}\text{Hf}, \(^{169}\text{Tm(}^{160,3p3n})^{172}\text{Lu} \) have been measured in the energy range \(71-95\text{ MeV}\}. The measured cross sections are tabulated in Table II. It may be pointed out that reactions \(^{169}\text{Tm(}^{160}\text{O,3n)}^{182}\text{Ir}, \(^{169}\text{Tm(}^{160,4n})^{181}\text{Ir}, \(^{169}\text{Tm(}^{160,p2n})^{182}\text{Os}, \) and \(^{169}\text{Tm(}^{160,p3n})^{181}\text{Os} \) may be populated only via CF. However, the reactions \(^{169}\text{Tm(}^{160,2p2n})^{181}\text{Re}, \(^{169}\text{Tm(}^{160,2p2n})^{178}\text{Re}, \(^{169}\text{Tm(}^{160,2p2n})^{178}\text{Hf}, \) and \(^{169}\text{Tm(}^{160,3p3n})^{172}\text{Lu} \) may be populated not only by CF but also by ICF.

In the interaction of heavy ions with a target nucleus, some of the residues are produced directly (independent yield) while some of them are also produced in the decay of a higher charge isobar precursor (cumulative yield) nucleus through \(\beta\) emission, and/or electron capture. For such cases, cumulative cross sections have 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 or about eight to ten half-lives of the precursor. The cumulative cross section of a given residue is the sum of (i) its independent production cross section and (ii) the 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 analysis given by Cavinato et al. [15] has been used to separate the contribution from precursor decay.

This has been done for the residue \(^{182}\text{Os}, \) which may be formed via the reaction \(^{169}\text{Tm(}^{160,p2n}) \) and may also be populated by the \(\beta\) decay of higher charge isobar precursor \(^{182}\text{Ir} \) produced via the reaction \(^{169}\text{Tm(}^{160,3n}) \). As such, the measured activity of residue \(^{182}\text{Os} \) has contributions from the precursor decay also. In the present work, the precursor contribution for the reaction \(^{169}\text{Tm(}^{160,p2n}) \) has been separated and the cumulative as well as independent yields for this residue are given in Table II. The cross section for \(^{181}\text{Os} \) given in Table II is cumulative, since this residue produced via reaction \(^{169}\text{Tm(}^{160,3n}) \) may also be populated through the \(\beta\) decay of higher charge isobar pre-cursor \(^{181}\text{Ir} \) produced via reaction \(^{169}\text{Tm(}^{160,4n}) \). Since the \(\beta\) decay of \(^{181}\text{Ir} \) produces \(^{181}\text{Os} \) (105 min) and \(^{181}\text{Os} \) (2.7 min) isotopes, the shorter half-life isotope could not be measured. As such, the precursor contribution for \(^{181}\text{Os} \) could not be deduced.

III. ANALYSIS OF EXCITATION FUNCTIONS

The analysis of presently measured excitation functions has been performed using three different computer codes viz., ALICE-91 [11], CASCADE [12], and PACE2 [13]. In the following sections brief details of these codes along with their important parameters, etc. are discussed.

A. Analysis with Code ALICE-91

The code ALICE-91 [11] has been developed by 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 the Weisskopf-Ewing model [17], while the PE component is simulated using the Hybrid/Geometry Dependent Hybrid model [18]. In this code, the configuration of the initially excited number of particles and holes, also referred to as initial exciton number \(n_0\), is the starting point in any particle induced nuclear reaction. In code ALICE-91, the intermediate states of the system are characterized by the excitation energy \(E\) and number \(n_0\) 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. The code ALICE-91 calculates two-body nuclear transi-
tion rates using Pauli corrected free nucleon-nucleon scattering cross-section data. The actual mean free path (MFP) inside the nucleus may be quite different from the one calculated using free nucleon-nucleon scattering data. In order to compensate for this difference, a parameter COST is provided in the code ALICE-91. A value of COST greater than zero means a smaller value of actual MFP for nucleon-nucleon scattering inside a composite excited nucleus. As such, in this code the level density parameter $a$, the mean free path multiplier COST and initial exciton number $n_0$ are the important parameters. The level density parameter $a$ largely affects the equilibrium component, while the initial exciton number $n_0$ and mean free path multiplier COST govern the pre-equilibrium component. The level density parameter $a$ is calculated from the expression $a=A/K$, where $A$ is the mass number of the residual nucleus and $K$ is a parameter which can be varied to match the experimental data. In this work, a value of $K=22$ along with $n_0=16(8p+8n+0h)$ and $COST=2$, is found to reproduce the maximum magnitude of the experimental data satisfactorily, but energy dependence could not compare well. It may be clarified that when ALICE-91 calculations with above mentioned values of parameters were compared with their experimental counterparts, it was observed that the maxima of the measured EF's were at higher energies than those of the 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 excitation function corresponding to the particle emission mode will be shifted to higher energies [19]. 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 the case of HI reactions. An estimate of the possible shift due to angular momentum effects may be made from the nuclear rotational energy. For a rigid body, the rotational energy is given by $E_{rot}=(n/M)E_{lab}$. Here, $m/M$ is the ratio of the projectile and the target nucleus masses and $E_{lab}$ is the incident energy [19]. Since the angular momentum effects have not been considered in the Weisskopf-Ewing calculations of the 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. Similar shift has been observed in some earlier work also [6-8]. As an example, the calculated EFs with an energy shift equal to $E_{rot}$ for reaction $^{169}$Tm($^{16}$O,$\alpha$3n)$^{182}$Ir is shown in Fig. 2. The unshifted calculated EF is also shown by a dotted curve in this figure for comparison. As such, in the present work, the calculated excitation functions for all the reactions have been shifted by $E_{rot}$ on the energy scale as shown in Figs. 3 and 4 by dashed curves. It may be mentioned that the nucleus $^{181}$Ir is found to emit about 34 $\gamma$-rays, the relative intensities of which are given in the reference [16]. In the present measurements, the residual nucleus $^{181}$Ir has been identified through $\gamma$-rays of energies 106.7 keV, 123.5 keV, 184.6 keV, 227 keV, 231.6 keV, and 318.9 keV. The absolute intensities of above mentioned $\gamma$-rays were calculated using relative intensity data of reference [16] and are given in Table I. It has been observed that the measured cross-section data agree with the theoretical calculations of code ALICE-91, as shown in Fig. 3(b). In Figs. 3(c) and 3(d) the experimentally measured and theoretically calculated EF's for the reactions $^{169}$Tm($^{16}$O,$\beta$2n)$^{182}$Os, and $^{169}$Tm($^{16}$O,$\beta$3n)$^{181}$Os are shown. The residue $^{182}$Os may be populated independently as well as by the $\beta^+$ decay of its higher charge isobar precursor $^{183}$Ir which may be formed via the reaction $^{169}$Tm($^{16}$O,3n). The open circles in Fig. 3(c) represent the cumulative yield for the production of the residue $^{182}$Os. A brief detail of the method used for separating precursor contribution [15] is given here.

If a precursor $P$ is formed with cross-section $\sigma_P$ during the irradiation, and decays with half-life $T_{P/2}$ 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 $T_{D/2}$, the cumulative cross-section $\sigma_C$ for the production of a daughter is given by

$$\sigma_C = \sigma_D + \sigma_P \left[ \frac{T^{0}_{D/2}}{T^{0}_{D/2} - T^{0}_{P/2}} \right] P_P. \quad (2)$$

Using the above formulation in the present case, the cumulative yield $\sigma_{cum}$ and independent yields $\sigma_{ind}$ are related by the equation

$$\sigma_{cum} = \sigma_{ind}(^{182}\text{Os}) + 1.011709\sigma(^{183}\text{Ir}). \quad (3)$$

The filled circles in Fig. 3(c) represent the observed independent yield of $^{182}$Os as discussed above. As can be seen from Fig. 3(d), there is a discrepancy between the measured and calculated EF for the reaction $^{169}$Tm($^{16}$O,$\alpha$3n)$^{181}$Os, which may be due to the contribution from its precursor decay. The observed enhancement, in Figs. 4(a) and 4(b), of measured

---

**FIG. 2.** The experimentally measured and theoretically calculated EFs using code ALICE-91. The calculated EF with an energy shift equal to $E_{rot}$ is shown by a solid curve, while unshifted EF is represented by a dotted curve for comparison.
FIG. 3. The experimentally measured and theoretically calculated EF's using codes ALICE-91, CASCADE, and PACE2. In (c), the open circles represent the cumulative yield for the production of the residue $^{187}\text{Os}$, while dark circles represent its independent yield.

EFs over their theoretically calculated values for the reactions $^{169}\text{Tm}(^{16}O,2p2n)^{181}\text{Re}$ and $^{169}\text{Tm}(^{16}O,\alpha3n)^{178}\text{Re}$ may be attributed to the fact that these channels may be populated, not only by the CF of $^{16}O$ but may also have significant contributions from ICF (if $^{16}O$ breaks up into $\alpha$, $^9\text{Be}$ and $^{12}C$ fragments). It may be pointed out that incomplete fusion is not taken into account in the ALICE-91 calculations. Further, the theoretical calculations for reactions $^{169}\text{Tm}(^{16}O,2\alpha p\pi n)^{181}\text{Hf}$ and $^{169}\text{Tm}(^{16}O,3\alpha n)^{182}\text{Lu}$ are not shown in Figs. 4(c) and 4(d), since the calculated values of cross-sections for these cases are negligibly small (<0.01 mb). As such, it may be concluded that the major contribution to these reaction channels comes from the incomplete fusion.

B. Analysis with code CASCADE

The code CASCADE [12] is based on Hauser-Feshbach theory [20] and does not consider the possibility of incomplete fusion (ICF) and 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 $F_{\varphi}$ are the two important parameters which may be varied to match the experimental data. The 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 [21] for neutrons and protons and that of Satchler [22] for $\alpha$-particles. 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 an increase in excitation energy also increases the angular momentum, as such, the deformation of the nucleus due to the angular momentum effect may also be quite substantial. In these calculations, the deformation effects may be included by using an angular momentum dependent moment of inertia, which results into the deviation of the yrast line from that calculated assuming the nucleus to be a rigid sphere. The level density parameter $a_{\varphi}$ at the saddle point, which is obtained from the relation $a_{\varphi}=A/D_{AF}$, where, $A$ is the mass number of the compound nucleus and $D_{AF}$ is a parameter, has also been found to influence the calculated EF’s considerably. It has been observed that the parameter $D_{AF}$ has a considerable influence on calculated EFs in the higher energy region. Further, a value of $K=14$, $D_{AF}=14$ with $F_{\varphi}=0.85$ is found to give satisfactory agreement with experimental data. The CASCADE calculations in Figs. 3 and 4 are shown by dotted curves. As may be observed from these Figs. 3(a) and 3(b), the EFs for $^{169}\text{Tm}(^{16}O,3n)^{182}\text{Ir}$ and $^{169}\text{Tm}(^{16}O,4n)^{181}\text{Ir}$ reactions are in
satisfactory agreement with theoretical calculations of code CASCADE. For reaction \(^{166}\text{Tm}(^{16}O,p2n)^{182}\alpha\text{Os}\), as can be seen from Fig. 3(c), the data peaks at a lower energy, and the predicted cross section is considerably larger than the calculation in the lower energy side. However, in case of reactions \(^{166}\text{Tm}(^{16}O,p3n)^{181}\alpha\text{Os}\) [Fig. 3(d)], the discrepancy between the experimental and calculated excitation function may be due to the pre-cursor contribution from the residue \(^{181}\text{Ir}\). The reaction \(^{166}\text{Tm}(^{16}O,2p2n)^{181}\text{Re}\) needs special mention. For this reaction, as shown in Fig. 4(a), theoretically calculated EFs do not match with the experimentally measured values. The theoretical calculations are much lower as compared to that of the experimentally measured EFs. This may be attributed to the fact that this channel may be populated not only by the CF of \(^{16}O\) but also may have a significant contribution from ICF. Further, for the reactions \(^{166}\text{Tm}(^{16}O,2apn)^{177}\text{Hf}\) and \(^{166}\text{Tm}(^{16}O,3an)^{172}\text{Lu}\), the calculated values of EFs using code CASCADE are negligibly small (<0.01 mb) and could not be shown in Figs. 4(c) and 4(d). 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. Further, the EF for the residue \(^{178}\text{Re}\) [Fig. 4(b)], which is expected to have a significant ICF component is reproduced well by this code which is quite surprising. In order to confirm the production of \(^{178}\text{Re}\) via an ICF channel, the recoil range distribution for this residue has also been measured and details are given in Sec. IV of this paper, which clearly indicates that ICF has a significant contribution for this channel.

C. Analysis with code PACE2

The code PACE2 [13] is based on a statistical approach. In this code the deexcitation of the CN is followed by a Monte Carlo procedure. The angular momentum projections are calculated at each stage of deexcitation which enables the determination of 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. In the present work, a value of level density parameter constant \(K=16\) is taken for calculation. The calculated EFs for the reactions \(^{169}\text{Tm}(^{16}O,3n)^{182}\alpha\text{Ir}\), \(^{169}\text{Tm}(^{16}O,4n)^{181}\alpha\text{Ir}\), \(^{169}\text{Tm}(^{16}O,p2n)^{183}\alpha\text{Os}\), and \(^{169}\text{Tm}(^{16}O,p3n)^{181}\alpha\text{Os}\) are shown in Figs. 3(a)–3(d). As can be seen from these figures that PACE2 calculations are in good agreement for the reactions.
COMPLETE AND INCOMPLETE FUSION REACTIONS IN...

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TABLE III. List of catcher-thicknesses used in RRD measurements.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Thickness in $\mu g/cm^2$</th>
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</thead>
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</tr>
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The recoil range distributions (RRDs) for various radioactive residues produced in the interaction of the 86.6 MeV $^{16}O$ beam with the $^{169}Tm$ target nucleus have been measured. The target was mounted in the irradiation chamber 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 about 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 16–45 $\mu g/cm^2$ was used to trap the recoiling nuclides. The thicknesses of the Al-catcher foils used are given in Table III. The duration of irradiation was about 18 h with a beam fluence of about 3500 $\mu C$. The activities induced in each catcher were followed off-line for about two weeks using a pre calibrated high resolution (2 keV for 1.33 MeV $\gamma$ ray of $^{60}Co$) HPGe detector of 100 c.c. active volume coupled to CAMAC based software FREEDOM [14] at NSC, New Delhi.

The cross-sections ($\sigma$) for a particular reaction product were computed using Eq. (1) as given in Sec. II. In order to obtain the yield distribution as a function of cumulative depth in the catcher stack, the cross section in each catcher was divided by its measured thickness. The resulting yields have been plotted in Figs. 5(a)–5(h) against cumulative catcher thickness to obtain the differential recoil range distributions. Solid curves guide the eye to the experimental data. As can be seen from the Figs. 5(a)–5(c), the recoil range distributions for $^{182}Ir$ and $^{186}Os$ isotopes produced via $^{16}O, 3n$, $^{16}O, p3n$, and $^{16}O, p2n$ channels, respectively, have a peak at only one value of cumulative catcher thickness $\approx 350 \mu g/cm^2$. Here, RRD of Ir and Os isotopes are nearly Gaussian having peaks at a depth nearly corresponding to the expected recoil range of the compound system $^{182}Ir$ in aluminum, calculated using the classical approach and the stopping power tables of Northcliffe and Schilling [23]. It means that these products (Ir and Os) are formed by a complete fusion process only, followed by the evaporation of $n$ and/or $p$. However, for reaction $^{169}Tm(16O, 2p2n)^{181}Re$ [Fig. 5(d)], the RRD has two peaks: one at a relatively lower value ($\approx 250 \mu g/cm^2$) of cumulative catcher thickness and the other at $\approx 350 \mu g/cm^2$, the same as in the case of complete fusion, respectively. In Fig. 5(d) the maxima at a larger value of cumulative thickness ($\approx 350 \mu g/cm^2$) corresponds to the fraction of the residues produced through complete fusion, while the peak at relatively smaller 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 of $^{12}C$, where the linear momentum transferred is expected to be less than that for the CF channel. In Fig. 5(e), it may be pointed out that the expected data points for the peak position of RRD at $\approx 350 \mu g/cm^2$ for the residue $^{172}Re$ produced via the $^{16}O, a3n$ reaction through CF could not be obtained due to the short half-life (13.3 m) of the residue. However, from the trend of RRD it may be observed that there may be two peaks: one corresponding to the ICF and the other due to the CF channel.

As expected, the observed recoil range distribution [Fig. 5(f)] for the $^{175}Hf$ isotope produced via $^{169}Tm(16O, 2apn)$ reaction 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., (a) the complete fusion of $^{16}O$ with $^{169}Tm$, forming the composite nucleus $^{181}Ir$, followed by the emission of a proton, a neutron and two $\alpha$-particles; (b) the 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 $\alpha$-particles; (c) the incomplete fusion of $^{16}O$, assuming that $^{16}O$ breaks up into two $^{12}Be$ fragments and one of these fragments fuses with $^{169}Tm$, forming the composite nucleus $^{177}Ta$, followed by the emission of a proton, and a neutron. For the reactions.
FIG. 5. The experimentally measured recoil range distributions for various radioactive residues produced in the interaction of an $^{16}\text{O}$ beam with a $^{169}\text{Tm}$ target at $\approx 87$ MeV.

$^{169}\text{Tm}(^{16}\text{O},3\alpha)^{172}\text{Lu}$ and $^{169}\text{Tm}(^{16}\text{O},3\alpha 2n)^{171}\text{Lu}$, the measured RRDs [Figs. 5(g) and 5(h)] show two peaks at relatively lower values of cumulative catcher thicknesses at $\approx 75 \mu g/cm^2$ and $\approx 150 \mu g/cm^2$, respectively. This indicates that these products are not populated by the complete fusion process but by some other process in which the linear momentum transferred is less than that for complete fusion process. This is possible when only a part of the projectile
Fig. 6. (Color online) The recoil range distributions fitted with Gaussian peaks for determining the relative contributions of complete and incomplete fusion.

V. CONCLUSIONS

Excitation functions for eight reactions in the $^{16}$O + Tm system have been measured. Theoretical calculations based on three different computer codes with a suitable choice of the various parameters agree well with the experimental data, in general. The pre-cursor-decay has been found...
to have significant contribution for p2n and p3n channels. The pre-cursor decay contribution has been obtained for the reaction $^{169}$Tm($^{16}$O, p2n)$^{182}$Os. The enhancement of experimentally measured cross sections for alpha emission channels over their theoretical predictions have been attributed to the fact that these residues are not only formed by the complete fusion but also through incomplete fusion. The RRDs for eight residues produced in the $^{16}$O+$^{169}$Tm system have also been measured. The analysis of RRD has clearly indicated the significant contribution of ICF. An attempt has been made to obtain the relative contribution of CF and ICF channels from the analysis of the measured RRD distributions.

**ACKNOWLEDGMENTS**

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[14] FREEDOM, Data acquisition and analysis system designed to support the accelerator based experiments at the Nuclear Science Centre, New Delhi, India.
A STUDY OF EXCITATION FUNCTIONS FOR SOME RESIDUES PRODUCED IN THE SYSTEM $^{14}\text{N} + ^{128}\text{Te}$ IN THE ENERGY RANGE $\approx 64-90$ MeV

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The excitation functions for eight reactions produced in the interaction of $^{14}\text{N} + ^{128}\text{Te}$ have been measured in the energy range $\approx 64-90$ MeV using the activation technique. To the best of our knowledge these measurements have been performed for the first time. The measured excitation functions are compared with theoretical calculations done using the computer programs ALICE-91 and PACE. The effect of the variation of various program parameters on calculated excitation functions have been studied. The present analysis indicates that complete fusion, incomplete fusion and pre-equilibrium emission processes play important roles in these reactions.

Keywords: Complete and incomplete fusion; activation technique; excitation functions; $^{14}\text{N} + ^{128}\text{Te}$ system; energy $\approx 64-90$ MeV.

1. Introduction

With the availability of accelerated beams of heavy ions, the study of nuclear reactions initiated by them has acquired a central place in nuclear physics research. Possible reaction mechanisms in heavy ion (HI) reactions at energies around the Coulomb barrier to well above it have been discussed in recent papers. In HI reactions, the formation of the compound nucleus (CN) is the dominant process at lower excitation energies. However, at moderate excitation energies, there are
indications that pre-equilibrium (PE) emission also contributes to the reaction processes. Experimental studies have shown that complete fusion (CF) and incomplete fusion (ICF) (Inamura et al. first identified incomplete fusion) also play important roles in HI reactions. In the case of CF reactions, the projectile completely fuses with the target nucleus, while in the case of ICF, only a part of the incident ion fuses with the target nucleus and the remaining part moves in the direction of the incident beam with almost the same velocity. CF and ICF processes may also be categorized on the basis of the degree of linear momentum transferred from the incident projectile to the composite system. In the former case, the entire linear momentum of the projectile is transferred to the target nucleus and in the latter, only a part of the projectile fuses with the target nucleus leading to fractional transfer of linear momentum. The fraction of the momentum transferred depends on the mass of the fused fragment.

Several measurements including measurements by our group have indicated the importance of CF and ICF as well as of PE-emission in HI reactions at energies around the Coulomb barrier. As a part of an ongoing program to study CF, ICF and PE-emission in HI reactions, the excitation functions (EFs) for eight reactions produced in the \(^{14}\text{N} + ^{128}\text{Te}\) system have been measured in the energy range \(64-90\) MeV. The experiments were performed using the 15 UD Pelletron accelerator facility at the Nuclear Science Centre (NSC), New Delhi, India. The experimental details are given in Sec. 2. The measured EFs are compared with theoretical calculations based on computer programs ALICE-91 and PACE. Results of the present analysis are presented in Sec. 3.

2. Experimental Details

Samples of \(^{128}\text{Te}\) of thickness 0.92 mg/cm\(^2\) were prepared from the enriched isotope of \(^{128}\text{Te}\) (\(\approx 87\%\)) by vacuum evaporation on aluminum foils of thickness 6.75 mg/cm\(^2\). The thickness of the samples was determined by measuring the energy loss of 5.485 MeV \(\alpha\)-particles from a \(^{241}\text{Am}\) source while passing through the target. The samples were fixed on aluminum holders of size 1.2 \(\times\) 1.2 cm\(^2\) with concentric circular holes of 10 mm diameter at their centers. The irradiations were performed in the General Purpose Scattering Chamber (GPSC) of 1.5 m diameter with a in-vacuum transfer facility at the NSC, New Delhi, India. Six samples of \(^{128}\text{Te}\) were irradiated individually by a \(^{14}\text{N}\)^{5+}/6+ beam at energies 64, 71, 76, 81, 86 and 90 MeV. The beam currents of \(\approx 5\) pnA were employed for irradiation. Keeping in view the half-lives of interest, the duration of each irradiation was kept at \(\approx 3\) hours. A sketch of the typical experimental arrangement used for irradiation is shown in Fig. 1. The two silicon surface barrier detectors \(D_1\) and \(D_2\) (Rutherford monitors) were kept at 30\(^\circ\) with respect to the direction of the beam at the forward angle to record the scattered incident ions for flux normalization. The incident flux was also determined from the total charge collected in the Faraday cup. The flux of the incident beam determined from the counts of the Rutherford monitors and
from the integrated current counts of the Faraday cup were found to agree with each other within 5%.

The γ-ray spectra of irradiated samples were recorded by a pre-calibrated CANBERRA HPGe detector of 100 c.c. active volume coupled to an ORTEC's PC based multi-channel analyzer. The spectrometer was calibrated using an $^{152}$Eu source. In order to measure short-lived activities, samples were quickly taken out from the scattering chamber using the in-vacuum transfer facility. The sample-detector separation was suitably adjusted so as to keep the dead time ≤ 5%. The counting of irradiated samples was performed for several days. Reaction residues were identified by their characteristic γ-rays as well as half-lives.

The cross-section $\sigma_r(E)$ at a given energy $E$ for different reactions was determined using the expression,$^{12}$

$$\sigma_r(E) = \frac{C \lambda e^{\lambda t}}{N_0 \xi \phi \theta G \epsilon (1 - e^{-\lambda t})(1 - e^{-\lambda t})},$$

where $C$ is the total number of observed counts in time $t$, $\lambda$ the decay constant of the activity, $t_t$ the time lapse between the end of the irradiation and the start of the counting, $N_0$ is the number of target nuclei irradiated in the time interval $t$, $\xi = \{ (1 - e^{-\mu d})/\mu d \}$ is the correction for self absorption of the γ-ray with absorption coefficient $\mu$ for the sample of thickness $d$. $\phi$ is the incident flux, $\theta$ the branching ratio of identified γ-ray, and $G \epsilon$ the geometry dependent efficiency of the detector for a particular energy $E$.

The errors in the measured cross-sections may be introduced because of the uncertainty in determining the efficiency of the detector, the dead time of the detector, uncertainty in determining the number of nuclei in the sample, fluctuations
in beam current, etc. The overall error from these factors including statistical error is found to be \( \leq 15\% \). A detailed discussion of these is given elsewhere.\(^{16}\)

3. Results and Discussion

The excitation functions for the reactions \( ^{128}\text{Te} (^{14}\text{N}, 4n)^{138m}\text{Pr} \), \( ^{128}\text{Te} (^{14}\text{N}, 5n)^{137}\text{Pr} \), \( ^{128}\text{Te} (^{14}\text{N}, p4n)^{137}\text{Ce} \), \( ^{128}\text{Te} (^{14}\text{N}, a5n)^{133}\text{La} \), \( ^{128}\text{Te} (^{14}\text{N}, o6n)^{132}\text{Nd} \), \( ^{128}\text{Te} (^{14}\text{N}, o2pn)^{135m}\text{Cs} \), \( ^{128}\text{Te} (^{14}\text{N}, 2a2pn)^{131}\text{I} \) and \( ^{128}\text{Te} (^{14}\text{N}, 3a)^{130}\text{I} \) have been measured in the beam energy range \( \approx 64-90 \) MeV. A list of reactions, residues detected, identified \( \gamma \)-ray energies, their abundances etc., are given in Table 1. All the spectroscopic data have been taken from Ref. 17. Experimentally measured cross-sections for the production of various residues are given in Table 2. To the best of our knowledge these measurements have been done for the first time and hence no data is available for comparison. The measured EFs have been compared with theoretical predictions based on computer programs ALICE-91\(^{14}\) and PACE.\(^{15}\) The details of these calculations and the parameters used are discussed in the following.

3.1. Analysis with ALICE-91

This code, developed by M. Blann,\(^{18}\) is based on the Weisskopf–Ewing model\(^{19}\) for CN calculations and the Hybrid Model\(^{20}\) for simulating PE-emission. The code assumes equipartition of energy among the initially excited particles and holes. The

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Residue</th>
<th>( J^* )</th>
<th>( E_\gamma ) (keV)</th>
<th>Abundance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ^{128}\text{Te} (^{14}\text{N}, 4n) )</td>
<td>( ^{128m}\text{Pr} )</td>
<td>7(^-)</td>
<td>302.7</td>
<td>80.0</td>
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<td>390.9</td>
<td>6.1</td>
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<td></td>
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<td>100</td>
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<td></td>
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<td></td>
<td>1037.8</td>
<td>100</td>
</tr>
<tr>
<td>( ^{128}\text{Te} (^{14}\text{N}, 5n) )</td>
<td>( ^{137}\text{Pr} )</td>
<td>5/2(^+)</td>
<td>434.3</td>
<td>1.3</td>
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<td>( ^{133}\text{La} )</td>
<td>5/2(^+)</td>
<td>302.4</td>
<td>1.2</td>
</tr>
<tr>
<td>( ^{128}\text{Te} (^{14}\text{N}, o6n) )</td>
<td>( ^{132}\text{Nd} )</td>
<td>2(^-)</td>
<td>540.4</td>
<td>7.8</td>
</tr>
<tr>
<td>( ^{128}\text{Te} (^{14}\text{N}, o2pn) )</td>
<td>( ^{135m}\text{Cs} )</td>
<td>19/2(^-)</td>
<td>786.9</td>
<td>99.7</td>
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<td></td>
<td></td>
<td>840.0</td>
<td>96.0</td>
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<tr>
<td>( ^{128}\text{Te} (^{14}\text{N}, 2a2pn) )</td>
<td>( ^{131}\text{I} )</td>
<td>7/2(^+)</td>
<td>364.4</td>
<td>81.2</td>
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<td></td>
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<td></td>
<td>637.0</td>
<td>7.3</td>
</tr>
<tr>
<td>( ^{128}\text{Te} (^{14}\text{N}, 3a) )</td>
<td>( ^{130}\text{I} )</td>
<td>5(^+)</td>
<td>536.1</td>
<td>99.0</td>
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<td>668.6</td>
<td>96.1</td>
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<td>739.5</td>
<td>82.3</td>
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A Study of Excitation Functions for Some Residues Produced

Table 2. Experimentally measured cross-sections for the residues.

<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma^{128mPr}$ (mb)</th>
<th>$\sigma^{137Pr}$ (mb)</th>
<th>$\sigma^{137m}Ce$ (mb)</th>
<th>$\sigma^{123La}$ (mb)</th>
<th>$\sigma^{129La}$ (mb)</th>
<th>$\sigma^{135mCa}$ (mb)</th>
<th>$\sigma^{131I}$ (mb)</th>
<th>$\sigma^{130I}$ (mb)</th>
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<tr>
<td>64 ± 0.8</td>
<td>225 ± 55</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>71 ± 0.8</td>
<td>381 ± 42</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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</tr>
<tr>
<td>76 ± 0.7</td>
<td>178 ± 20</td>
<td>456 ± 65</td>
<td>144 ± 19</td>
<td>—</td>
<td>—</td>
<td>46 ± 4</td>
<td>—</td>
<td>2 ± 0.5</td>
</tr>
<tr>
<td>81 ± 0.6</td>
<td>62 ± 8</td>
<td>463 ± 60</td>
<td>194 ± 21</td>
<td>—</td>
<td>—</td>
<td>6 ± 0.6</td>
<td>—</td>
<td>28 ± 4</td>
</tr>
<tr>
<td>86 ± 0.5</td>
<td>66 ± 7</td>
<td>577 ± 62</td>
<td>220 ± 35</td>
<td>376 ± 38</td>
<td>18 ± 2</td>
<td>1 ± 0.1</td>
<td>98 ± 32</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>90 ± 0.5</td>
<td>48 ± 5</td>
<td>611 ± 72</td>
<td>263 ± 50</td>
<td>1435 ± 144</td>
<td>478 ± 48</td>
<td>141 ± 40</td>
<td>36 ± 4</td>
<td>2 ± 0.3</td>
</tr>
</tbody>
</table>

The ALICE-91 code uses Gove mass tables\textsuperscript{21} or the Myers Swiatecki/Lysekil\textsuperscript{22} mass formula. The option that substitutes Gove's table\textsuperscript{21} for Myers Swiatecki/Lysekil\textsuperscript{22} mass formula including shell corrections was used. In order to calculate inverse cross-sections, the optical model subroutine with the parameters of Becchetti and Greenlees\textsuperscript{23} was employed.

The important parameters of the ALICE-91 code are the level density parameter $\alpha$, initial exciton number $n_0$, and the mean free path multiplier $COST$. The first parameter greatly affects the equilibrium component, through the level densities. The level density parameter $\alpha$ is calculated using the relation $\alpha = A/K$, where $A$ is the mass number of the compound system and $K$ is a constant which may be varied to match the experimental data. The effect of the variation of $K$ on the calculated EFs was also studied. The value of $K$ was varied from 9 to 18. As a typical example, the calculated EFs for the reaction $^{128}\text{Te}(^{14}\text{N},4n)$ for different values of $K$ are shown in Fig. 2(a). As can be seen from this figure, and in general also, the present experimental data is best reproduced with a value of $K = 18$. The parameters $n_0$ and $COST$ greatly govern the PE-component. The initial exciton number $n_0$ decides the complexity of the initial configuration. A smaller value of $n_0$ means that the initial state is less complex and hence far from the equilibrium. As such, a larger PE-contribution is expected. On the other hand, a large value of $n_0$ means that the system is nearer to the equilibrium stage and therefore, smaller PE-contribution is likely. In order to see the effect of variation of $n_0$ on calculated EFs, calculations were done by varying $n_0$ from 14 to 16. As a representative case, these calculations for $^{128}\text{Te}(^{14}\text{N},4n)$ channel are shown in Fig. 2(b). It may be seen from this figure that a value of $n_0 = 14$ is best suited for the present experimental data. The value of $n_0 = 14$ may be justified assuming that the projectile $^{14}\text{N}$ breaks up in the nuclear field of the target nucleus creating 14 excitons. The parameter $COST$, which is used to adjust the mean free path for two-body residual interactions inside the nuclear matter, is varied from 1 to 4 and its effect on EF for $^{128}\text{Te}(^{14}\text{N},4n)$ reaction is shown in Fig. 2(c). As a representative case. It may be pointed out that a set of $K = 18$, $n_0 = 14$ with $COST = 1$ gives a satisfactory reproduction of the magnitude of the experimental data, in general. Similarly, the EF for the $^{128}\text{Te}(^{14}\text{N},5n)$ reaction is shown in Fig. 2(d), and is satisfactorily reproduced in magnitude by the chosen set of parameters.
It has, however, been observed that theoretically calculated excitation functions for all the reactions presently studied with the above set of parameters have their maxima shifted towards the lower energies, as compared to the experimental data.

Fig. 2 Excitation functions for the reactions $^{128}\text{Te}({}^{14}\text{N},4\text{n})^{138}\text{m}_{\text{Pr}}$, $^{128}\text{Te}({}^{14}\text{N},5\text{n})^{137}\text{Pr}$ and $^{128}\text{Te}({}^{14}\text{N},p4\text{n})^{137}\text{Ce}$. The filled circles represent the experimental data. Various curves correspond to the theoretical predictions of the ALICE-91 code.
This is expected as in HI induced reactions the projectile imparts large angular momentum to the composite system. As such, this high angular momentum imparted to the composite system, may inhibit particle emission in the last stages of de-excitation. As a result, the peaks of the experimental EFs corresponding to a particle emission mode are expected to be shifted towards higher energies. An estimate of the possible energy shift may be obtained from the rotational energy $E_{\text{rot}}$, which may be approximated using $E_{\text{rot}} \approx (m/M)E_{\text{lab}}$, where $m$ and $M$ are, respectively, the projectile and target masses, and $E_{\text{lab}}$ is the incident energy.

In the regime of incident energies considered in the present work, the rotational energy shift ($E_{\text{rot}}$) is found to vary from $\approx 7-9$ MeV. Since, the angular momentum effects have not been taken into account in Weisskopf–Ewing calculations, it is desirable to shift the calculated EFs by an amount $\approx E_{\text{rot}}$. As such, theoretically calculated EFs for all the reactions were shifted towards high energies side by an amount $\approx E_{\text{rot}}$ and satisfactory agreement between experimental and theoretical EFs has in general, been observed. As a representative case, the effect of rotational energy on calculated EF for the reaction $^{128}\text{Te}(^{14}\text{N},4\alpha)$ is shown in Fig. 2(e).

In Fig. 2(f), experimentally measured cross-sections for the reaction $^{128}\text{Te}(^{14}\text{N},p4\alpha)$ are shown along with theoretically calculated EFs. As can be seen from this figure, even by varying the level density parameter constant $K (= 9-18)$, the theoretical calculations always underestimate the cross-sections as compared to the experimental data, particularly at higher energies. These larger values of observed cross-sections may be due to the contribution from precursor decay. During irradiation of the sample, the residual nucleus $^{137}\text{Ce}$ may be populated via two different channels. Firstly, directly through the reaction $^{128}\text{Te}(^{14}\text{N},p4\alpha)$, and secondly, through the $\beta^+$ decay of the residual nucleus $^{137}\text{Pr}$ formed via the reaction $^{128}\text{Te}(^{14}\text{N},5\alpha)$. As such, the measured cross-sections of the $^{128}\text{Te}(^{14}\text{N},p4\alpha)$ reaction will have a contribution from the $\beta^+$ decay of the higher charge isobar precursor (cumulative yield) also. Although it is possible to estimate the contribution from precursor decay, this could not be done in the present case, since the metastable state of the $^{137}\text{Ce}$ ($t_{1/2} = 34.4$ hours) could not be observed.

In Fig. 3(a), the experimentally measured EF of the $^{128}\text{Te}(^{14}\text{N},4\alpha)$ reaction is compared with the theoretical calculations done by considering only the CN model as well as by including the PE-component. The dashed line in this figure gives the calculation done by considering the Weisskopf–Ewing model. As can be seen from this figure, the CN calculations do not match with the experimental data at high energies, where PE-emission may be important. In order to see the effect of PE-emission, theoretical calculations were also performed using the hybrid model option of the ALICE-91 program. It can be seen from Fig. 3(a), that the high energy tail portion of the measured EF is close to the calculated EF, if PE-emission is included in the calculations. As such, it may be concluded that there is a substantial PE-component in the reaction $^{128}\text{Te}(^{14}\text{N},4\alpha)$ at higher energies, as expected.
Fig. 3. Excitation functions for the reactions $^{128}\text{Te}(^{14}\text{N},4\text{n})^{132}\text{mPr}$, $^{128}\text{Te}(^{14}\text{N},5\text{n})^{133}\text{La}$, $^{128}\text{Te}(^{14}\text{N},6\text{n})^{133}\text{yLa}$, $^{128}\text{Te}(^{14}\text{N},2\text{pn})^{133}\text{mCs}$, $^{128}\text{Te}(^{14}\text{N},2\alpha2\text{pn})^{131}\text{I}$ and $^{128}\text{Te}(^{14}\text{N},3\alpha)^{130}\text{y}$.

The filled circles represent the experimental data. The solid and dotted lines correspond to the theoretical predictions of the ALICE-91 code.
For the $^{128}\text{Te}(^{14}\text{N},\alpha 5\pi n)$ and $^{128}\text{Te}(^{14}\text{N},\alpha 6\pi n)$ reactions, the theoretical predictions of code ALICE-91 give substantially small cross-sections as compared to the measured cross-sections shown in Figs. 3(b) and (c), respectively. This discrepancy of considerably higher experimentally measured cross-sections as compared to the theoretical calculations may be explained in terms of the contribution coming from the ICF of the $^{14}\text{N}$ ion. If it is assumed that the $^{14}\text{N}$ ion breaks up into $^{10}\text{B}$ and $^4\text{He}$ fragments under the nuclear field of the target nucleus and if only one of the two fragments fuses, i.e. $^{10}\text{B}$ ($^4\text{He}$ moves along the beam direction), fuses with the target nucleus forming the excited composite system $^{138}\text{La}$, the excited $^{138}\text{La}^*$ may then emit $5\pi n/6\pi n$ leading to the formation of the residual nuclei $^{133}\text{La}$ and $^{132}\text{La}$, respectively. Theoretical calculations from ALICE-91, however, do not take this ICF process into account. As such, the discrepancy in the experimentally measured EFs and the theoretically calculated counterparts may be attributed to the above mentioned ICF processes.

In the case of the $^{128}\text{Te}(^{14}\text{N},\alpha 2\pi 2\pi n)$, $^{128}\text{Te}(^{14}\text{N},2\alpha 2\pi n)$ and $^{128}\text{Te}(^{14}\text{N},3\alpha)$ reactions, theoretical predictions from ALICE-91 give negligible cross-sections while the measured experimental cross-sections are substantial, as shown in Fig. 3(d)-(f). This discrepancy of much higher experimentally measured cross-sections as compared to the theoretical calculations may again be explained in terms of the contributions coming from incomplete fusion of the $^{14}\text{N}$ ion. The higher cross-sections in the case of $^{128}\text{Te}(^{14}\text{N},\alpha 2\pi n)$ reactions may be explained assuming that $^{10}\text{B}$ (if $^{14}\text{N}$ breaks up into $^{10}\text{B}$ and $^4\text{He}$) fuses with the target nucleus and emits two protons and a neutron. Similarly, the reaction $^{128}\text{Te}(^{14}\text{N},2\alpha 2\pi n)$ may be understood assuming the break up of $^{14}\text{N}$ into $^6\text{Li}$ and two $\alpha$-particles, where $^6\text{Li}$ fuses with the target nucleus emitting two protons and a neutron. Further, in the case of the $^{128}\text{Te}(^{14}\text{N},3\alpha)$ reaction it may be assumed that the $^{14}\text{N}$ breaks up into three $\alpha$-particles and a deuteron, where fusion of $^2\text{H}$ takes place with the target nucleus leaving behind the residual nucleus $^{130}\text{I}$, which may decay by $\gamma$-emission. Since theoretical calculations from ALICE-91 do not take the ICF process into account, it may be inferred that a significant part of the reaction in these cases goes through ICF.

3.2. Analysis with PACE

The PACE program is based on a statistical approach. In this program, the deexcitation of the CN is followed by a 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. The level density parameter is an important parameter, which may be varied to match the experimental data. The effect of variation in the level density parameter constant $K$ (= 8, 9, 10 and 11) on calculated EFs for the reactions $^{128}\text{Te}(^{14}\text{N},4\pi n)$, $^{128}\text{Te}(^{14}\text{N},5\pi n)$ and $^{128}\text{Te}(^{14}\text{N},p4\pi n)$ are shown in Figs. 4(a)-(c). As can be observed from these figures, a value of $K = 11$ satisfactorily reproduces the measured EFs, in general,
Fig. 4. Excitation functions for the reactions $^{128}\text{Te}(^{14}\text{N},4\text{n})^{132}\text{SmPr}$, $^{128}\text{Te}(^{14}\text{N},5\text{n})^{137}\text{Pr}$, $^{128}\text{Te}(^{14}\text{N},4\text{p}4\text{n})^{137}\text{Ce}$, $^{128}\text{Te}(^{14}\text{N},5\text{n})^{132}\text{La}$, $^{128}\text{Te}(^{14}\text{N},6\text{n})^{132}\text{La}$ and $^{128}\text{Te}(^{14}\text{N},\alpha2\text{pn})^{135}\text{Cs}$. The filled circles represent the experimental data. Various curves correspond to the theoretical predictions of the PACE code.
A Study of Excitation Functions for Some Residues Produced

EXPERIMENTAL

(a)

(b)

Fig. 5. Excitation function for the reactions \(^{128}\text{Te}^{(14\text{N},2\alpha2pn)}^{131}\text{I}\) and \(^{128}\text{Te}^{(14\text{N},3\alpha)}^{130}\text{I}\). The filled circles represent the experimental data.

for \(^{128}\text{Te}^{(14\text{N},4n)}\) and \(^{128}\text{Te}^{(14\text{N},5n)}\) channels, which are populated via complete fusion. Further, as can be seen from Fig. 4(c), the experimental values are larger as compared to their theoretical counterparts. As in the case of ALICE-91 calculations also, it may be because of the contributions from precursor decay as expected. As already mentioned, the precursor contribution in this case could not be separated as the meta stable state of \(^{137}\text{Ce}\) could not be observed.

Since ICF is not considered in these calculations, the enhancement of the measured EFs for reactions \(^{128}\text{Te}^{(14\text{N},\alpha5n)}\) and \(^{128}\text{Te}^{(14\text{N},\alpha6n)}\) as shown in Figs. 4(d) and (e) may be attributed to the fact that these isotopes are not only produced by complete fusion but also have a significant contribution from ICF (if \(^{14}\text{N}\) breaks up into \(^{10}\text{B}\) and \(^{4}\text{He}\) fragments). Further, the theoretical calculations give negligible cross-sections for the reactions \(^{128}\text{Te}^{(14\text{N},\alpha2pn)}\), \(^{128}\text{Te}^{(14\text{N},2\alpha2pn)}\), and \(^{128}\text{Te}^{(14\text{N},3\alpha)}\) while the experimental values are quite substantial as shown in Figs. 4(f), 5(a) and (b). As such, it may again be inferred that major contributions for the production of these isotopes come from ICF channels, which are not considered in these calculations.

From the analysis presented, it may be concluded that rotational energy shift, pre-equilibrium emission, complete and incomplete fusion processes play important roles in reactions induced by heavy ions. Further, in order to determine the relative contribution of CF and ICF channels, it is proposed to carry out the measurement of the recoil range and angular distributions of residues produced in the above systems.

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References

A study of the reactions occurring in $^{16}O + ^{159}Tb$ system: Measurement of excitation functions and recoil range distributions

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Abstract

In order to study complete and incomplete fusion in heavy ion reactions, the excitation functions for several residues produced in the system $^{16}O + ^{159}Tb$ have been measured in the energy range $\approx 70-95$ MeV, employing activation technique. The measured excitation functions have been compared with those calculated using computer codes CASCADE, PACE2 and ALICE-91. Comparison of measured and theoretically calculated excitation functions has indicated significant contributions from incomplete fusion in some $\alpha$-emission channels. In the present experiment, the recoil range distributions of several residues at $\approx 90$ MeV incident beam energy have also been measured using recoil catcher technique and off-line gamma ray spectrometry. Analysis of the recoil range distributions has further confirmed the presence of contributions from incomplete fusion reactions. An attempt has been made to separate out the relative contributions of complete and
incomplete fusion channels.

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1. Introduction

Study of nuclear reactions induced by heavy ions (HIs) is a topic of current interest. There are various ways of classifying the reaction mechanism involved in HI interaction. On the basis of the impact parameter of the interacting ions, it is possible to distinguish the various kind of reactions involved in HI interaction[1]. At very large values of impact parameter (energy of incident ion below the Coulomb barrier), the projectile interacts only through the Coulomb field leading to the distant collision. If the impact parameter is comparable to the sum of the radii of interacting HIs, grazing collision takes place and the projectile can be elastically or inelastically scattered. As the value of the impact parameter decreases, the projectile interacts with the target nucleus at relatively high energy just enough to enter in the nuclear range of the interacting nuclei under consideration, then the deep inelastic collision (DIC) dominates. In such a case, the nuclear densities rise very rapidly in the surface region, and a few nucleons may get transferred from one nucleus to the other. Further, at still smaller values of impact parameter, the projectile interacts with the target very strongly and the phenomena like complete fusion (CF) and incomplete fusion (ICF) may take place. Thus, broadly speaking, at moderate excitation energies and at relatively lower values of impact parameters, HI reaction mechanism may be classified into CF and ICF processes. In case of CF, the projectile is completely absorbed by the target nucleus, forming an excited composite system from which nuclear particles and/or $\gamma$-rays may be emitted subsequently. However, in case of ICF, the incident ion is assumed to break up into the fragments in the vicinity of nuclear field of the target nucleus, followed by fusion of one of
the fragments with the target nucleus, while the remaining part of projectile goes on moving almost along the beam direction with approximately beam velocity. The excited system formed as a result of the fusion of a fragment of the incident ion may undergo de-excitation by the emission of nuclear particles and/or gamma rays. Measurement and analysis of excitation functions [2, 3] in HI reactions have indicated that ICF is an important component of reaction mechanism at moderate excitation energies. Pre-equilibrium (PE) emission of nucleons from the composite system has also been observed in some cases[2].

During the last few years there has been renewed interest in the study of ICF mechanism at beam energies as low as 6 MeV/nucleon [4, 5, 6]. The ICF reactions may be studied from the analysis of excitation functions (EFs), recoil range distribution (RRD) and angular distribution of the evaporation residues. Such measurements are still limited to a few systems only. As such, to have a better understanding of CF and ICF processes, more experimental data on EFs and RRD of the residues in HI reactions, covering a wide range of the target-projectile pair and energy is required. Further, the dependence of relative strength of CF & ICF processes on energy and projectile-target combination is still not well understood and no systematic study has been performed. From the study of RRD of the residues, the relative contribution of CF and ICF components and their dependence on energy and projectile-target combination may be explored. The measurements of RRD of the residue is based on the momentum transfer of the projectile to the target nucleus. In CF process, momentum of the projectile is completely transferred to the target nucleus. Thus, the composite system carries the entire lin-
ear momentum and hence travels a larger distance in the stopping medium. However, in case of ICF reaction, partial transfer of projectile momentum takes place, the composite system formed due to partial fusion of projectile travels relatively a smaller distance in the stopping medium. In the present work the recoil range distribution technique has been used to determine the CF and ICF contributions in a given reaction. Most of the studies, where occurrence of ICF was observed even at lower beam energies, were carried out generally with medium-mass targets. Though, initial studies on ICF have been carried out at energies ≈10 MeV/nucleon using rare-earth targets\cite{7, 8}, there are limited studies with heavier targets having $A > 150$. Further, when medium mass targets are used, it becomes difficult to distinguish the residues produced by CF and ICF mechanisms, as $\alpha$-emission from the fused excited system is quite pronounced. However, if heavier targets are used, the emission of $\alpha$-particles from the fused excited system is likely to be substantially reduced\cite{9} due to high Coulomb barrier. As a result, the emission of $\alpha$-particles in ICF channels may give rise to heavy residues which have very little contribution from CF channels. The evaporation residues formed in these reactions are known to have permanent deformation, however, the statistical model calculations consider only the dynamical deformation due to high excitation energy and rotation. Nicolis et. al.,\cite{10} have indicated that static deformation may give rise to higher probability of alpha-emission from the composite system. However, the present measurements of recoil range distribution of the residues formed via alpha emission channels have indicated that the major contribution to these channels, in general, may come from ICF process, as discussed in details in section 4 of the paper. With a view to study
CF and ICF reactions in several projectile-target combinations, a programme of precise measurement of EFs and RRDs has been undertaken[11, 12]. In the present work, measurement of EFs for reactions $^{159}\text{Ta}^{(16}\text{O},3\text{n})^{172}\text{Ta}$, $^{159}\text{Ta}^{(16}\text{O},4\text{n})^{171}\text{Ta}$, $^{159}\text{Ta}^{(16}\text{O},5\text{n})^{170}\text{Ta}$, $^{159}\text{Ta}^{(16}\text{O},p3\text{n})^{171}\text{Hf}$, $^{159}\text{Ta}^{(16}\text{O},p4\text{n})^{170}\text{Hf}$, $^{159}\text{Ta}^{(16}\text{O},2p2\text{n})^{171}\text{Lu}$, $^{159}\text{Ta}^{(16}\text{O},\alpha\text{n})^{170}\text{Lu}$, $^{159}\text{Ta}^{(16}\text{O},\alpha2\text{n})^{169}\text{Lu}$, and $^{159}\text{Ta}^{(16}\text{O},2\alpha2\text{n})^{168}\text{Tm}$ in the incident energy range $\approx 70-95$ MeV have been presented. The measured EFs have been compared with theoretical predictions based on CASCADE[13], PACE2[14] and ALICE-91[15] codes. The RRDs of several residues have also been measured for the same system at $\approx 90$ MeV beam energy by collecting the recoiling residues in thin Al-catcher foils of varying thicknesses. To the best of our knowledge these measurements are being reported for the first time. Experimental details are discussed in section 2 of the paper, while the analysis of EFs and RRDs are given in sections 3 & 4, respectively. Conclusions are given at the end of the paper.

2 Experimental

2.1 Excitation functions

The beam of oxygen ions of charge state 7$^+$ obtained from the 15 UD Pel­letron accelerator facility of the Nuclear Science Center (NSC), New Delhi, India, has been used to carry out the present experiments using activation technique. One of the main advantages of the activation technique is that in a single irradiation, cross-sections for a large number of reactions may be measured. The details of sample preparation, irradiation of samples, calibra-
tion of gamma spectrometer and post-irradiation analysis are given in the following parts.

2.1.1 Sample preparation

The spectroscopically pure self-supporting foils of $^{159}$Tb (purity $\approx 99.99\%$) were rolled in order to obtain desired thickness of samples. The thickness of each target was determined from the measurement of the energy lost by 5.485 MeV $\alpha$ particles of $^{241}$Am source, while passing through the sample. The measured thicknesses of the $^{159}$Tb foils were $\approx 1.8 \text{ mg/cm}^2$. The samples were cut into size of $1.2 \times 1.2 \text{ cm}^2$ each and were pasted on rectangular Al-holders having concentric holes of 1.0 cm diameter. The Al-holders were used for rapid heat dissipation. The Al-degraders kept between two successive $^{159}$Tb samples served both as energy degrader as well as catcher foils.

2.1.2 Irradiation

Two stacks containing four $^{159}$Tb samples each, were irradiated by $^{16}O^{7+}$ beam at 90 and 95 MeV respectively, in the General Purpose Scattering Chamber (GPSC) of 1.5 m diameter, having in-vacuum transfer facility. The beam currents were $\approx 50 \text{ nA}$. The irradiation of two stacks covered the desired energy range $\approx 70-95 \text{ MeV}$. The targets of $^{159}$Tb backed by Al-catcher of thickness $\approx 2 \text{ mg/cm}^2$ were placed normal to the beam direction so that the recoiling nuclei coming out of the target may be trapped in the catcher foil. Keeping in view the half lives of interest, the irradiations were carried out for $\approx 8 \text{ hours} \text{ duration each}$. The delay time between the stop of irradiation and the beginning of counting was minimised using in-vacuum transfer of sam-
samples from the scattering chamber to the counting system. The total charge collected in the Faraday cup was used to calculate the flux of the incident beam. In an auxiliary experiment the flux of the incident beam determined from the charge collected in the Faraday cup was compared with that calculated from the Rutherford monitors held at ±30° with respect to the beam direction. The two readings of the flux agreed with each other within the uncertainty of about 5%.

2.1.3 Calibration of spectrometer and post-irradiation analysis

The activities induced in various samples were recorded by counting the target and catcher foils together using HPGe γ-ray spectrometer coupled to a PC based multichannel analyser employing FREEDOM software[16]. The HPGe detector (resolution ≈ 2 keV for 1.33 MeV γ-ray of ⁶⁰Co) was pre-calibrated both for energy and efficiency employing various standard γ sources like ²²Na, ⁵⁴Mn, ⁵⁷,⁶⁰Co, ¹³³Ba, ¹³⁷Cs and ¹⁵²Eu. Typical plots of the photo peak efficiency of HPGe detector as a function of γ-rays energies varying from 121 keV to 1408 keV using ¹⁵²Eu point source for various source-detector separations are shown in Fig.1. Observed γ-ray spectrum of irradiated ¹⁵⁹Tb sample at 95 MeV is shown in Fig. 2. Various peaks in observed γ-ray spectrum were assigned to different reaction residues on the basis of their characteristic energy of γ-lines as well as measured half lives. A list of reactions, energy of identified γ-rays and their branching ratios are given in Table 1. The measured intensities of the characteristic γ-rays were
used to compute the reaction cross sections using the formulation [11],

\[ \sigma_r(E) = \frac{C_o \lambda \exp(\lambda t_i)}{N_o \phi PK(G_e)[1 - \exp(-\lambda t_i)][1 - \exp(-\lambda t_o)]} \]  

where, \( C_o \) is the observed counts during the accumulation time \( t_o \) of the induced activity of decay constant \( \lambda \), \( N_o \) the number of target nuclei irradiated for time \( t_i \) with a particle beam of flux \( \phi \), \( t_i \) the time lapse between the stop of irradiation and the start of counting, \( P \) the branching ratio of the characteristic \( \gamma \) ray and \( G_e \) the geometry dependent efficiency of the detector for the \( \gamma \) ray of a given energy. The value of \( G_e \) depends on the energy of the \( \gamma \) ray and also on the relative separation between the source and detector. In order to determine the value of \( G_e \) for \( \gamma \) rays of different energies, a standard source of \(^{152}\text{Eu}\) of known strength was used. The experimentally determined values of \( G_e \) for various source-detector distances and for \( \gamma \) rays of different energies are already shown in Fig.1. As such, proper correction for the geometry dependent efficiency has been taken into account for each case. The factor \([1 - \exp(-\lambda t_i)]\), known as the saturation correction takes care of the decay of evaporation residues during the irradiation. The corrections for the decay of the induced activity due to the delay between the stop of irradiation and the start of counting and during the data accumulation are taken into account via the factors \( \exp(\lambda t_i) \) and \([1 - \exp(-\lambda t_o)]\) respectively.

\[ K = [1 - \exp(-\mu z)]/\mu z \] is the correction for the self absorption of the \( \gamma \) radiation in the sample thickness itself, where \( z \) is the thickness of the sample and \( \mu \) is the \( \gamma \) ray absorption coefficient.

Excitation functions for the reactions

\[ ^{159}\text{Tb}[^{16}\text{O}, 3n]^{172}\text{Ta}, \]
\[ ^{159}\text{Tb}[^{16}\text{O}, 4n]^{171}\text{Ta}, \]
\[ ^{158}\text{Tb}[^{16}\text{O}, 5n]^{170}\text{Ta}, \]
\[ ^{158}\text{Tb}[^{16}\text{O}, p3n]^{171}\text{Hf}, \]

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$^{159}Tb^{(16\,O,p4n)}^{170}Hf$, $^{159}Tb^{(16\,O,2p2n)}^{171}Lu$, $^{159}Tb^{(16\,O,\alpha2n)}^{169}Lu$ and $^{159}Tb^{(16\,O,2\alpha2n)}^{165}Tm$ have been measured in the energy range $\approx$70-95 MeV and are tabulated in Table 2. These excitation functions are plotted in Figs.(3-10). As is obvious the residues $^{175-x}Ta$, $(x=3-5)$ and $^{175-x}Hf$, $(x=4\&5)$ are populated only via CF. However, the residues $^{175-x}Lu$, $(x=4-6)$ and the residue $^{165}Tm$ may have contributions not only from CF but also from ICF channels.

In the interaction of $^{16}O$ ions with the target nucleus $^{159}Tb$ some of the residues may be produced directly (independent yield) while some of them are also produced by the decay of higher charge isobar precursor (cumulative yield) nucleus through $\beta^+$ emission, and/or electron capture. For such cases, cumulative cross sections have 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 precursor. The cumulative cross section $\sigma_c$ of a given residue is the sum of (i) its independent production cross section $\sigma_i$ and (ii) cross section for the independent production of its precursor $\sigma_p$ multiplied by a numerical coefficient $F_p$[17],

$$\sigma_c = \sigma_i + F_p \sigma_p$$

(2)

The value of $F_p$ depends on the branching ratio $P_p$ for precursor decay to the residue and is given below,

$$F_p = P_p \frac{T_i}{T_i - T_p}$$

(3)

here, $T_p \& T_i$ are the half lives of the precursor and the residue. As such, the
cumulative cross-section is given by,

\[ \sigma_c = \sigma_i + P_p \frac{T_i}{T_i - T_p} \sigma_p \]  \hspace{1cm} (4)

The residues \(^{171,170}\text{Hf}\) may be formed by the reactions \(^{159}\text{ Tb}(^{16}O, p3n)\) & \(^{159}\text{ Tb}(^{18}O, p4n)\) respectively and may also be populated by the \(\beta^+\) decay of higher charge isobar precursors \(^{171,170}\text{Ta}\) produced via the reactions \(^{159}\text{ Tb}(^{16}O, 4n)\) & \(^{159}\text{ Tb}(^{16}O, 5n)\). As such, the measured activity of residues \(^{171,170}\text{Hf}\) has contribution from their precursors also. The values of branching ratios and the half lives required for obtaining the coefficients \(F_p\) are taken from the reference[18]. Using the above formulation (4) in the present case, the cumulative yield \((\sigma_c)\) and independent yield \((\sigma_i)\) for \(^{171}\text{Hf}\) are related by the equation;

\[ \sigma_c(^{171}\text{Hf}) = \sigma_i(^{171}\text{Hf}) + 1.03315 \sigma_p(^{171}\text{Ta}) \]  \hspace{1cm} (5)

here, \(\sigma_p(^{171}\text{Ta})\) is the independent yield of the precursor.

Attempt has also been made to separate out the independent yield of the residue \(^{170}\text{Hf}\) produced via \(p4n\) channel. The cumulative \((\sigma_c)\) and independent yields \((\sigma_i)\), for the residue \(^{170}\text{Hf}\) are related by the equation;

\[ \sigma_c(^{170}\text{Hf}) = \sigma_i(^{170}\text{Hf}) + 1.007047 \sigma_p(^{170}\text{Ta}) \]  \hspace{1cm} (6)

here, \(\sigma_p(^{170}\text{Ta})\) is the independent yield of the precursor. The measured cross-sections for cumulative as well as independent production for the residues \(^{171}\text{Hf} & ^{170}\text{Hf}\) are given in Table 2.

3 Analysis
cumulative cross-section is given by,

$$\sigma_c = \sigma_i + P_p \frac{T_i}{T_p} \sigma_p$$  \hspace{1cm} (4)

The residues $^{171,170}Hf$ may be formed by the reactions $^{159}Tb(^{16}O, p3n)$ & $^{159}Tb(^{16}O, p4n)$ respectively and may also be populated by the $\beta^+$ decay of higher charge isobar precursors $^{171,170}Ta$ produced via the reactions $^{158}Tb(^{16}O, 4n)$ & $^{159}Tb(^{18}O, 5n)$. As such, the measured activity of residues $^{171,170}Hf$ has contribution from their precursors also. The values of branching ratios and the half lives required for obtaining the coefficients $F_p$ are taken from the reference[18]. Using the above formulation (4) in the present case, the cumulative yield ($\sigma_c$) and independent yield ($\sigma_i$) for $^{171}Hf$ are related by the equation;

$$\sigma_c(^{171}Hf) = \sigma_i(^{171}Hf) + 1.03315 \sigma_p(^{171}Ta)$$  \hspace{1cm} (5)

here, $\sigma_p(^{171}Ta)$ is the independent yield of the precursor.

Attempt has also been made to separate out the independent yield of the residue $^{170}Hf$ produced via $p4n$ channel. The cumulative ($\sigma_c$) and independent yields ($\sigma_i$), for the residue $^{170}Hf$ are related by the equation;

$$\sigma_c(^{170}Hf) = \sigma_i(^{170}Hf) + 1.007047 \sigma_p(^{170}Ta)$$  \hspace{1cm} (6)

here, $\sigma_p(^{170}Ta)$ is the independent yield of the precursor. The measured cross-sections for cumulative as well as independent production for the residues $^{171}Hf & ^{170}Hf$ are given in Table 2.

3 Analysis
The analysis of presently measured excitation functions has been performed using three different computer codes viz., CASCADE\[13\], PACE2[14] and ALICE-91[15]. In the following sections brief details of these codes along with their important parameters etc., are discussed.

3.1 Analysis with code CASCADE

The code CASCADE[13] is based on Hauser-Feshbach theory[19]. It does not consider the possibility of incomplete fusion (ICF) and PE emission. The decay probabilities are determined by the level densities of the daughter nuclei and the barrier penetrabilities for the various channels. The optical model potentials of Becchetti and Greenlees [20] are used for calculating the transmission coefficients for protons and neutrons, and optical model potential of Satchler [21] is used for α particles. Fermi gas model is used for calculating the level densities for the product nuclei.

The partial cross-section for the formation of the compound nucleus of spin \( J \) and parity \( \pi \) from a projectile and a target nucleus of spins \( J_P \) and \( J_T \) respectively, at center of mass energy \( E \) is given by [22],

\[
\sigma(J, \pi) = \frac{\pi\lambda^2}{4\pi^2} \frac{(2J + 1)}{(2J_P + 1)(2J_T + 1)} \sum_{S=|J_P - J_T|L=|J - S|}^{J_P + J_T} \sum_{J + S} T_L(E) \tag{7}
\]

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

The total fusion cross-section for the maximum angular momentum \( L_c \) of
the compound nucleus is given by,

\[ \sigma_L = \frac{\pi \lambda^2}{4\pi^2} \sum_{L=0}^{L_c} (2L + 1)T_L(E) \]  \hspace{1cm} (8)

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

\[ I = \frac{2}{5}mr^2 \]  \hspace{1cm} (9)

where, \( r \) is the radius of spherical nucleus given by \( r_c A^{1/3} \).

The level density formula implies a yrast line,

\[ E_{rot}(J) = \frac{J(J+1)\hbar^2}{2I} + \Delta \]  \hspace{1cm} (10)

where, \( \Delta \) is pairing energy which determines the zero point of the effective excitation energy. In this code the level density parameter constant \( K \) and the ratio of actual moment of inertia to the rigid body moment of inertia of the excited system \( F_0 \) are the two important parameters which may be varied to match the experimental data. In HI induced reactions the high angular momentum and excitation energy are expected to have considerable influence on the de-excitation cascade. Since in HI reactions increasing excitation energy also increase the angular momentum, as such, 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 may be obtained from the relation $a_f = A/D_{AF}$, where, $A$ is the mass number of the compound nucleus and $D_{AF}$ is a free parameter, may be varied to match the experimental data. It has been observed that the parameter $D_{AF}$ has considerable influence on calculated EFs in the higher energy region. The effect of variation in the values of level density parameter constant $K$ on the calculated EFs for the reactions $^{159}\text{Tb}(^{16}O, 3n)^{172}\text{Ta}$, $^{159}\text{Tb}(^{16}O, 4n)^{171}\text{Ta}$, $^{159}\text{Tb}(^{16}O, 5n)^{170}\text{Ta}$ and $^{169}\text{Yb}(O, p3n)^{171}Hf$ are shown in Figs. 3 (a-d) along with the measured cross-sections. The effect of variation in the values of level density parameter $a_f$ at the saddle point, which may be obtained from the relation $a_f = A/D_{AF}$, where, $A$ is the mass number of the compound nucleus and $D_{AF}$ is a free parameter, may be varied to match the experimental data. It has been observed that the parameter $D_{AF}$ has considerable influence on calculated EFs in the higher energy region. The effect of variation in the values of level density parameter constant $K$ on the calculated EFs for the reactions $^{159}\text{Tb}(^{16}O, 3n)^{172}\text{Ta}$, $^{159}\text{Tb}(^{16}O, 4n)^{171}\text{Ta}$, $^{159}\text{Tb}(^{16}O, 5n)^{170}\text{Ta}$ and $^{169}\text{Yb}(O, p3n)^{171}Hf$ are shown in Figs. 3 (a-d) along with the measured cross-sections. 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code CASCADE particularly in the peak region. The measured EFs for the reactions $p3n$ and $p4n$ are found to be much higher than the predictions of the code CASCADE. The discrepancy between the measured and calculated EFs may be attributed to the contribution from pre-cursor decay, which is also not considered in this code. Using the equation (4), attempt has been made to separate out the contribution from pre-cursor decay and it has been observed that the deduced independent yields for $^{171}Hf$ agree well with the calculations of code CASCADE as shown in Fig 3(d). However, it is surprising that for residue $^{170}Hf$, the similar procedure could not match the data, as shown in Fig. 4(a). The reaction $^{159}Tb(^{16}O,2p2n)^{171}Lu$ [Fig. 4(b)] needs special mention. The residue $^{171}Lu$ may be formed by the emission of two protons and two neutrons from the compound system, which may have contribution from its precursor isobars $^{171}Ta$ and $^{171}Hf$. The same residue ($^{171}Lu$) may also be formed by the incomplete fusion of $^{16}O$ ion (if $^{12}C$ may fuse with the target nucleus). Thus the observed enhancement by several orders of magnitude over its theoretical predictions for reaction $^{159}Tb(^{16}O,2p2n)^{171}Lu$ may not only be attributed to the pre-cursor decay but also from incomplete fusion. As can be seen from the Figs. 4(c&d) for reactions $^{159}Tb(^{16}O,\alpha n)^{170}Lu$ and $^{159}Tb(^{16}O,\alpha 2n)^{169}Lu$ experimentally measured EFs do not match with the theoretical values. The theoretical calculations are lower by few orders of magnitude compared to that of the experimental data. This discrepancy 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 $\alpha$ and $^{12}C$ fragments). Further, for the reaction $^{159}Tb(^{16}O,2\alpha 2n)^{165}Tm$, the calculated
values of EFs using code CASCADE are negligibly small (< 0.01 mb) and could not be shown in Fig. 5. Since, the ICF has not been considered in CASCADE calculations, it may be concluded that the major contribution to this reaction channel comes from the incomplete fusion.

3.2 Analysis with code PACE2

The code PACE2[14] is based on statistical approach. In this code the de-excitation of the CN is followed by Monte Carlo procedure. The angular momentum projections are calculated at each stage of de-excitation which enables the determination of angular distribution of the emitted particles. The CF cross-sections are calculated using Bass formula[24]. The optical model parameters for neutron, proton and α-emission were used as default value in the code[14]. The γ-ray strength functions for E1, E2 and M1 transition were taken from tables of Endt[25]. In this code the level density parameter given by \( \alpha = A/K \), is one of the important parameters, where, \( A \) is the mass number of the compound nucleus and \( K \) is a free parameter. The value of \( K \) may be varied to match the experimental data. The effect of variation of level density parameter constant \( K \) of this code on calculated EFs for reactions \(^{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}, \(^{160}\text{Tm} (O, p3n)^{171}\text{Hf} \) and \(^{160}\text{Tm} (O, p4n)^{170}\text{Hf} \) are shown in Figs. 6(a-d) and Fig. 7 (a). A value of \( K = 8 \), (default value), is found to satisfactorily reproduce the measured EFs, in general. In Fig 5(d) and 6(a) the independent and cumulative yields are plotted and are compared with the calculations done using code PACE2. In case of reactions \(^{159}\text{Tb} (^{16}\text{O}, 2p2n)^{171}\text{Lu}, \(^{159}\text{Tb} (^{16}\text{O}, \alpha n)^{170}\text{Lu}, \(^{159}\text{Tb} (^{16}\text{O}, \alpha 2n)^{169}\text{Lu} \) and \(^{159}\text{Tb} (^{16}\text{O}, 2\alpha 2n)^{165}\text{Tm} \), the
calculated values are smaller than the measured cross-sections as shown in Figs. 7(b-d) and Fig. 8. The enhancement of the measured cross-sections over their calculated values may be due to the ICF process.

3.3 Analysis with Code ALICE-91

The code ALICE-91[15] developed by M. Blann, may be used to calculate the equilibrium (CN) as well as pre-equilibrium (PE) emission cross-sections in light and heavy ion induced reactions. The CN calculations in this code are performed using Weisskopf-Ewing model[27], while, PE component is simulated using Geometry Dependent Hybrid model[28]. In this code the possibility of incomplete fusion is not taken into account. The particles which could be emitted are neutron, proton, deuteron and/or α particles. The code may calculate the reaction cross-sections for the residual nuclei upto 11 mass and 9 atomic number units away from the compound nucleus. Myers-Swiatecki/Lysekil mass formula [29] 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 [30] subroutines, although there is also an option of classical sharp cut off model. The transmission coefficients are calculated using the parabolic model of Thomas [31] for heavy ions. Calculations for PE-emission in this code are done assuming equipartition of energy among the initial excited particles and holes. The mean free path (MFP) for intranuclear transition rates may be calculated either from the optical potential parameters of Becchetti and Greenlees [20] or from Pauli corrected nucleon-nucleon cross-sections [32, 33]. In the present calculations the optical potentials of Becchetti and Greenlees [20] have been used.
Level densities of the residue in code ALICE-91 may be calculated either from the Fermi Gas model or from the constant temperature form. The Fermi gas model gives [34],

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

(11)

where, \( \delta \) is the pairing term and \( U \) is the excitation energy of the nucleus. The level density parameter \( a \) is taken as \( A/K \), \( A \) being the mass number of the nucleus and \( K \) is an adjustable parameter. The level density \( \rho(U) \) in constant temperature form is given as [35],

\[
\rho(U) \propto \frac{1}{T} \varepsilon^{U/T}
\]

(12)

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 \( \nu \)):

\[
\frac{d\sigma}{d\varepsilon} = \frac{\pi \lambda^2}{4\pi^2} \sum_{I=0}^{\infty} (2I + 1) T_I (2S_\nu + 1) \sum_{J=|I-I|}^{I+1} T^I_\nu(\varepsilon) \sum_{J=|I-I|}^{I+1} \rho(\varepsilon, J) / D
\]

(13)

where, \( \lambda \) is the de-Broglie wavelength of the incident ion, \( T_I \) the transmission coefficient of the \( I^{th} \) partial wave of the incident ion, \( \rho(\varepsilon, J) \) 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. However, the heavy ion projectile imparts large angular momentum to the composite system having a finite moment of inertia and hence greater rotational energy. Due to nuclear rotation, a nucleus with a given angular momentum $J$, can not have energy below a minimum value $E_J^{min}$,

$$E_J^{min} \approx J(J + 1) \frac{\hbar^2}{2I}$$  \hspace{1cm} (14)

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

In this code the level density parameter $a$, the mean free path multiplier $COST$ and initial exciton number $n_0$ are some of the important parameters. The level density parameter $a$ largely affects the equilibrium component, while the initial exciton number $n_0$ and mean free path multiplier $COST$ govern the pre-equilibrium component. The level density parameter $a$ is calculated from the expression $a=A/K$. In code ALICE-91, 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. In the present work a value of $n_0=16$ with configuration $(8p + 8n + 0h)$ has been found to satisfactorily reproduce the experimental data, where, $p$, $n$ and $h$ represent
the number of excited protons, neutrons and holes respectively. The code ALICE-91 calculates two-body nuclear transition rates using Pauli corrected free nucleon-nucleon scattering cross-section data. The actual mean free path (MFP) inside the nucleus may be quite different from the one calculated using free nucleon-nucleon scattering data. In order to compensate for this difference, a parameter COST is provided in the code ALICE-91. A value of COST greater than zero means, a smaller value of actual MFP for nucleon-nucleon scattering inside composite excited nucleus. In the present work, a value of COST=2, is found to reproduce the experimental data satisfactorily. When ALICE-91 calculations with above mentioned values of parameters were compared with their experimental counterpart, it was observed that the maxima of the measured EF's were at higher energies than those of the 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 excitation function corresponding to the particle emission mode will be shifted to higher energies [36]. 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 made from the nuclear rotational energy. For a rigid body, the rotational energy is given by $E_{\text{rot}} \approx (m/M)E_{\text{lab}}$. Here, m/M is the ratio of the projectile and the target nucleus masses and $E_{\text{lab}}$ is the incident energy[36]. Since the angular momentum effects have not
been considered in the Weisskopf-Ewing calculations of the 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. As such, in the present work, the calculated excitation functions have been shifted by $E_{rot}$ on the energy scale. As an example, the calculated EFs with an energy shift equal to $E_{rot}$ for reactions $^{159}Tb(^{16}O, 3n)^{172}Ta$, $^{159}Tb(^{16}O, 4n)^{171}Ta$, $^{159}Tb(^{16}O, 5n)^{170}Ta$ and $^{159}Tb(^{16}O, p3n)^{171}Hf$ are shown in Figs. 9(a-d), respectively. The unshifted calculated EF's are also shown by dotted lines in these figures for comparison. As may be observed the theoretically calculated EFs agree satisfactorily with the measured ones after incorporating rotational energy shifts for all cases, in general. It may be remarked that the excitation function for $^{159}Tb(^{16}O, Zny^{^9}Ta$ reaction could not be reproduced in the tail portion with a value of $K = 10$. Since this code also does not consider ICF into account, thus the observed enhancement, in Figs. 10(b-d) of measured EFs over their theoretically calculated values for the reactions $^{159}Tb(^{16}O, 2p2n)^{171}Lu$, $^{159}Tb(^{16}O, \alpha n)^{170}Lu$ and $^{159}Tb(^{16}O, \alpha 2n)^{169}Lu$ may be attributed to the fact that these channels may be populated not only by the CF of $^{16}O$ but may also have significant contributions from ICF (if $^{16}O$ breaks up into $\alpha$, $^8$Be and $^{12}$C fragments). Further, the theoretical calculations for reaction $^{159}Tb(^{16}O, 2\alpha 2n)^{165}Tm$ give the cross-sections which are negligibly small (< 0.01 mb) and hence no comparison is made. On the other hand the measured excitation function for this channel has substantial cross-sections. As such, it may be concluded that the major contribution to this reaction channel comes from the incomplete fusion.
at a depth corresponding to the expected recoil range in Aluminium for the compound system $^{175}Ta$. This indicates that these products ($Ta$&$Hf$) are formed by complete fusion process only.

It may be observed from Figs. 11(e-i), that the RRDs for the residues $^{175-2}Lu$, $x=4-6$ and $^{167,168}Tm$ have two peaks one at a relatively lower value ($\approx 250\mu g/cm^2$) of cumulative catcher thickness and the other at $\approx 350\mu g/cm^2$. The peak at $\approx 350\mu g/cm^2$ corresponds to the fraction of residues produced in the complete fusion. The peak at relatively smaller range of cumulative catcher thickness ($\approx 250\mu g/cm^2$) may be attributed to the fact that the residues $^{175-2}Lu$, ($x=4-6$) are produced via incomplete fusion of $^{16}O$ if $^{12}C$ is fused, where the linear momentum transferred is expected to be less than that for CF channel. It may be pointed out and can be seen from the Fig. 11 (e) that the measured RRD for the residue $^{171}Lu$ produced via reaction $^{159}Tb(^{16}O,2p2n)$ appear to have a peak structure similar to that of combination of two peaks. Here, the peak at lower value of cumulative catcher thickness ($\approx 250\mu g/cm^2$) corresponds to the fraction of the residues produced through incomplete fusion channel, while the peak at larger value of cumulative thickness ($\approx 350\mu g/cm^2$) [clearly shown in Fig. 11 (e)] corresponds to the fraction of the residues produced through complete fusion channel. As such this reaction may have contributions not only from CF but also have minor contribution from ICF.

As expected, the observed recoil range distribution [Fig. 11 (j)] for the $^{165}Tm$ isotope produced via $^{159}Tb(^{16}O,2\alpha 2n)$ reaction has three peaks at cumulative thicknesses $\approx 400\mu g/cm^2$, $\approx 300\mu g/cm^2$ and $\approx 200\mu g/cm^2$ corresponding to the residue $^{165}Tm$ produced via three different channels i.e., (a)
complete fusion of $^{16}O$ with $^{159}Tb$, forming the composite nucleus $^{175}Ta$, followed by the emission of two neutrons and two $\alpha$-particles, (b) 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 $^{159}Tb$, forming the composite nucleus $^{171}Lu$, followed by the emission of two neutrons and an $\alpha$-particles, (c) incomplete fusion of $^{16}O$, assuming that $^{16}O$ breaks up into two $^8Be$ fragments and one of these fragments fuses with $^{159}Tb$, forming the composite nucleus $^{167}Tm$, followed by the emission of two neutrons. In this case, two peaks at lower recoil ranges ($\approx 300 \mu g/cm^2$ & $\approx 200 \mu g/cm^2$) are due to two incomplete fusion channels ($^{12}C$ & $^8Be$).

Further, the measured RRD for the reaction $^{159}Tb(^{16}O,3\alpha)n$_{Ho} [Fig. 11 (k)] shows three peaks at relatively lower values of cumulative catcher thickness at $\approx 75 \mu g/cm^2$, $\approx 150 \mu g/cm^2$ and $\approx 270 \mu g/cm^2$, respectively. In this case the peak corresponding to the expected range ($\approx 350 \mu g/cm^2$) of CF channels has not been observed. Absence of the peak corresponding to the complete fusion channel, indicates that the reaction predominantly goes through ICF channels only.

In order to separate out the relative contributions of complete and incomplete fusion in these reactions, the experimentally measured RRDs have been fitted [Fig. 12(a-c)] with Gaussian peaks using the software ORIGINE. The software ORIGINE requires the observed intensity distribution of the RRDs and number of peaks to be fitted, as input data. The software then generates the gaussian peaks, with approximate FWHM to fit the data. The relative contributions of the CF and ICF processes are obtained by dividing the area of the corresponding peak by the total area. The relative
contributions of CF and ICF processes for reactions $^{159}Tb(^{16}O, 2\alpha n)^{168}Tm$, $^{159}Tb(^{16}O, 2\alpha 2n)^{165}Tm$ and $^{159}Tb(^{16}O, 3\alpha n)^{162}Tm$ are shown in Figs. 12(a-c). The relative contribution of incomplete fusion of $^{12}C$ for reaction $^{159}Tb(^{16}O, 2\alpha n)^{168}Tm$ [Fig. 12(a)] (shown by dotted curve) is found to be $\approx 70\%$, while the contribution from complete fusion (shown by solid curve) is $\approx 30\%$. Similarly, for reaction $^{159}Tb(^{16}O, 2\alpha 2n)^{165}Tm$ [Fig. 12(b)] the contributions of incomplete fusion of $^{12}C$ and $^8Be$ (shown by dash and solid curves) are found to be $\approx 38\%$ and $\approx 13\%$, respectively, while the contribution of complete fusion is $\approx 49\%$. Further, for reaction $^{159}Tb(^{16}O, 3\alpha n)^{162}Tm$ [Fig. 12(c)], contributions of three incomplete fusion of $^{12}C$, $^8Be$ & $\alpha$-particle are found to be $\approx 15\%$, $\approx 49\%$ & $\approx 36\%$, respectively with an uncertainty of $\approx 5\%$.

5. Conclusions

Excitation functions for nine reactions in $^{16}O + ^{159}Tb$ system have been measured. Theoretical calculations based on different computer codes with suitable choice of the parameters agree well with the experimental data, in general. The pre-cursor decay contribution has been obtained for the reactions $^{159}Tb(^{16}O, p3n)^{171}Hf$ and $^{159}Tb(^{16}O, p4n)^{170}Hf$. The RRDs for eleven residues produced for the same system at 90 MeV beam energy have also been measured. The analysis of RRD has clearly indicated the significant contribution of ICF channels. The relative contributions of ICF and CF channels have been separated for some cases using the RRD curves.

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References


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


Table Captions

Table 1. List of reactions, identified γ-rays and their branching ratios.
Table 2. The experimentally measured cross-sections for isotopes produced via complete fusion and incomplete fusion.
<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>$^{159}\text{ Tb}(^{16}\text{ O},3\text{n})^{172}\text{ Ta}$</td>
<td>213.9, 318.7</td>
<td>52.0, 4.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1085.5, 1109.2</td>
<td>7.6, 14.0</td>
</tr>
<tr>
<td>2.</td>
<td>$^{159}\text{ Tb}(^{16}\text{ O},4\text{n})^{171}\text{ Ta}$</td>
<td>152.2, 166.1</td>
<td>5.8, 19.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>175.1, 444.1,</td>
<td>16.0, 15.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>501.3, 506.1,</td>
<td>15.6, 54.0</td>
</tr>
<tr>
<td>3.</td>
<td>$^{159}\text{ Tb}(^{16}\text{ O},5\text{n})^{170}\text{ Ta}$</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>$^{159}\text{ Tb}(^{16}\text{ O},p3\text{n})^{171}\text{ Hf}$</td>
<td>122.0, 137.6</td>
<td>11.5, 12.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>295.6, 371.1</td>
<td>5.0, 5.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>662.2, 1071.8</td>
<td>5.6, 5.4</td>
</tr>
<tr>
<td>5.</td>
<td>$^{159}\text{ Tb}(^{16}\text{ O},p4\text{n})^{170g}\text{ Hf}$</td>
<td>120.1,</td>
<td>19.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>164.6, 620.6</td>
<td>33.0, 23.0</td>
</tr>
<tr>
<td>6.</td>
<td>$^{159}\text{ Tb}(^{16}\text{ O},2p2\text{n})^{171}\text{ Lu}$</td>
<td>667.0</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>739.8, 780.7</td>
<td>48.1, 4.3</td>
</tr>
<tr>
<td>7.</td>
<td>$^{159}\text{ Tb}(^{16}\text{ O},\alpha\text{n})^{170}\text{ Lu}$</td>
<td>193.1</td>
<td>2.07</td>
</tr>
<tr>
<td>8.</td>
<td>$^{159}\text{ Tb}(^{16}\text{ O},\alpha2\text{n})^{169}\text{ Lu}$</td>
<td>191.2</td>
<td>20.7</td>
</tr>
<tr>
<td>9.</td>
<td>$^{159}\text{ Tb}(^{16}\text{ O},2\alpha2\text{n})^{165}\text{ Tm}$</td>
<td>242.8, 296.0</td>
<td>35.0, 23.0</td>
</tr>
</tbody>
</table>
Figure Captions

Fig. 1. The photo peak efficiencies for various source-detector separation of HPGe detector as a function of $\gamma$-rays energies varying from 121 keV to 1408 keV using $^{152}$Eu point source.

Fig. 2. Observed $\gamma$-ray spectrum for $^{16}O + ^{159}Tm$ system at 95 MeV.

Figs. 3. The experimentally measured and theoretically calculated EFs using code CASCADE. The effect of variation of parameter K is also shown in these figures. In the Fig. 3(d), the open circles represent the cumulative yield for the production of the residue $^{171}$Hf, while solid circles represent its independent yield.

Figs. 4. The experimentally measured and theoretically calculated EF's using code CASCADE. In the Fig. 4(a), the open circles represent the cumulative yield for the production of the residue $^{170}$Hf, while dark circles represent its independent yield.

Figs. 5. The experimentally measured EFs.

Figs. 6. The experimentally measured and theoretically calculated EFs using code PACE2. The effect of variation of parameter K is also shown in these figures. In the Fig. 6(c), the open circles represent the cumulative yield for the production of the residue $^{171}$Hf, while solid circles represent its independent yield.

Figs. 7. The experimentally measured and theoretically calculated EFs using code PACE2. The effect of variation of parameter K is also shown in these figures. In the Fig. 7(a), the open circles represent the cumulative yield for the production of the residue $^{170}$Hf, while solid circles represent its
independent yield.

**Figs. 8.** The experimentally measured and theoretically calculated EFs using code PACE2.

**Figs. 9.** The experimentally measured and theoretically calculated EFs using code ALICE-91. The calculated excitation function with an energy shift equal to $E_{rot}$ are shown by solid lines in these figures for comparison. In the Fig. 9(c), the open circles represent the cumulative yield for the production of the residue $^{171}$Hf, while solid circles represent its independent yield.

**Figs. 10.** The experimentally measured and theoretically calculated EFs using code ALICE-91. In the Fig. 10(a), the open circles represent the cumulative yield for the production of the residue $^{170}$Hf, while solid circles represent its independent yield.

**Figs. 11.** The experimentally measured recoil range distributions for various radioactive residues produced in the interaction of $^{16}$O beam with $^{159}$Tb target at $\approx$90 MeV are shown.

**Figs. 12.** The recoil range distribution fitted with gaussian peaks for determining the relative contributions of complete and incomplete fusion
<table>
<thead>
<tr>
<th>Lab Energy (MeV)</th>
<th>$\sigma^{(172}Ta$ (mb)</th>
<th>$\sigma^{(171}Ta$ (mb)</th>
<th>$\sigma^{(170}Ta$ (mb)</th>
<th>$\sigma_{\text{cum}}^{(171}Hf$ (mb)</th>
<th>$\sigma_{\text{ind}}^{(171}Hf$ (mb)</th>
<th>$\sigma_{\text{cum}}^{(170}Hf$ (mb)</th>
<th>$\sigma_{\text{ind}}^{(170}Hf$ (mb)</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>
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<tbody>
<tr>
<td>69.4±1.0</td>
<td>0.334±0.08</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>75.0±0.9</td>
<td>19.8±3.3</td>
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<td>13.6±5.66</td>
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<tr>
<td>78.7±0.9</td>
<td>34.8±6.8</td>
<td>67.05±11.75</td>
<td>80.29±19.0</td>
<td>11.01±5.0</td>
<td>-</td>
<td>-</td>
<td>29.54±3.1</td>
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<td>4.24±0.47</td>
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<tr>
<td>83.2±0.8</td>
<td>48.14±5.5</td>
<td>280.5±47.0</td>
<td>64.91±6.6</td>
<td>431.2±86.2</td>
<td>141.4±56.63</td>
<td>84.65±10.0</td>
<td>19.23±2.3</td>
<td>61.63±6.5</td>
<td>6.54±1.05</td>
<td>76.84±11.28</td>
<td>5.53±0.58</td>
</tr>
<tr>
<td>87.2±0.8</td>
<td>12.65±2.2</td>
<td>244.0±43.3</td>
<td>100.27±15.4</td>
<td>322.02±74.4</td>
<td>69.93±29.9</td>
<td>177.32±20.0</td>
<td>76.34±11.8</td>
<td>1167.62±170.6</td>
<td>49.81±6.74</td>
<td>43.48±4.56</td>
<td>7.58±0.8</td>
</tr>
<tr>
<td>90±1.0</td>
<td>11.89±2.4</td>
<td>228.3±39.2</td>
<td>263.48±38.74</td>
<td>340.17±73.5</td>
<td>104.3±41.7</td>
<td>574.32±68.8</td>
<td>308.26±36.7</td>
<td>611.8±64.0</td>
<td>31.33±5.44</td>
<td>80.65±9.45</td>
<td>10.36±1.3</td>
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<tr>
<td>95±0.4</td>
<td>8.53±1.5</td>
<td>157.98±28.5</td>
<td>390.19±45.5</td>
<td>205.4±46.2</td>
<td>42.1±18.0</td>
<td>427.32±55.0</td>
<td>34.88±10.8</td>
<td>255.89±26.3</td>
<td>31.33±5.4</td>
<td>34.49±4.55</td>
<td>5.76±1.1</td>
</tr>
</tbody>
</table>
Fig. 1
Fig. 3
Fig. 4
Experimental

Fig. 5

$^{158}\text{Tb}({}^{16}\text{O}, 2\alpha 2n){}^{165}\text{Tm}$

sigma (mb)

Energy (MeV)
Fig. 6
Fig. 7
Fig. 8

$^{159}\text{Tb}(^{16}\text{O}, 2\alpha 2\text{n})^{165}\text{Tm}$

Experimenal

$K=8$

$K=10$

Energy (MeV)

$sigma$ (mb)
Fig. 9
Fig. 10
Fig. 11
Fig. 12