CHAPTER-1

INTRODUCTION

“Oh what idiots we all have been! Oh but this is wonderful! This is just as it must be! Have you and Lise Meitner written a paper about it?”

- Niels Bohr to Otto Frisch upon being told about the discovery of nuclear fission.

1.1 PROLOGUE

Understanding the fundamental nature of matter has been an exclusive pursuit of scientists since long. The studies in this regard got a great boost, with the discoveries of electron and radioactivity during the last decade of 19th century. Since then, the microscopic world of atomic nucleus has been explored intensively. In an atom, nucleus is a very small entity at the centre and consists of nucleons. The atomic nucleus was discovered, by Rutherford in 1911. The Rutherford-Bohr model of the atom was followed by the advent of quantum mechanics developed by physicists like de-Broglie, Schrödinger, Heisenberg, Pauli, Dirac and others. The consistent efforts on the experimental and theoretical fronts finally led to the present understanding of the nucleus and the atom. In an atomic nucleus, neutrons and protons are held together by strong attractive nuclear forces. Though, information on exact nature of nuclear forces is still limited and not established analytically, however, much progress has been made towards its phenomenological understanding. One way of getting this information is through the study of nuclear reactions. The nuclear reactions may be broadly categorized as elastic and inelastic reactions. In the former, interacting partners only change their direction of motion while in the latter, one or both of the interacting partners may change their internal states alongwith their nuclear properties. Since, the time scale involved in nuclear reactions is very short (≈10^{-22}-10^{-16} sec), therefore, it is not possible to visualize the process directly. In 1936, Danish physicist, Niels Bohr proposed the description of nuclear reaction on the basis of compound nucleus (CN) theory [1]. According to this theory, nuclear reaction is a two-stage process, (i) the formation of a relatively long-lived intermediate nucleus and its subsequent decay. Here, the incident nucleus loses all its energy to the target
nucleus and becomes an integral part of an excited compound nucleus (CN),
(ii) After a relatively long period of time (∼ 10^{-16} \text{ sec}) and independent of the
properties of the reactants, the compound nucleus disintegrates, usually into an
ejected small particle leaving behind a relatively heavier product nucleus. The CN
theory is based on the above description referred to as the ‘Bohr’s independent
hypothesis’. As a matter of fact, the lapse time between the formation of composite
system and its decay is too large, and hence, no trace is left to decide its mode of
formation [1]. The validity of independent hypothesis has been experimentally
verified by Ghoshal [2] in 1950, where the reaction cross-sections of almost same
orders of magnitude (within the experimental uncertainties) have been observed for
particular reaction products formed via different entrance channels. Further, the
discovery of fission opened another important area of nuclear reaction studies. The
process of fission was explained initially by applying the liquid drop model of the
nucleus realizing that it would be energetically favourable to split the heavy nucleus
into two fragments.

Over the years, the general features of nuclear fission reactions were
understood, however, the dynamics of fission still needs to be explored. The
availability of heavy ion particle accelerators, one at the Inter University Accelerator
Centre (IUAC), New Delhi and the other at the Tata Institute of Fundamental
Research (TIFR), Mumbai gave a boost to the study of HI induced fusion-fission
reactions in our country. It may be pointed out that, a large number of experimental
reports indicate that fission takes place from fully equilibrated compound nucleus
(CN) undergoing shape changes to reach a saddle configuration following statistical
rules. A detailed discussion on heavy ion induced reactions and how they are different
from light ion induced reactions is given here.

1.2 HEAVY-ION REACTIONS

The term heavy ion (HI) is generally used for the nuclei which are heavier
than helium. The heavy ion induced reactions are widely different from light ion
induced reactions because of the fact that both the projectile and the target nuclei are
many nucleon systems, consequently there is large natural electrostatic repulsion
between interacting partners. However, the energy and momentum carried by the heavy ions are relatively large. At energies $\approx$ a few tens of MeV, heavy ions have wavelength much less than nuclear radii so that in some respect their motion may be considered similar to that of a classical particle ($\lambda \ll R$). That is why in many cases of heavy ion reactions, the collisions are explained on the basis of classical theory [3].

A typical classical picture of heavy ion collisions is given in Fig. 1.1. According to classical picture, broadly there may be three types of collisions, which may be described on the basis of impact parameter ‘$b$’ or the corresponding angular momentum ‘$l$’. As can be seen from Fig. 1.1, at projectile energies deep below the fusion barrier ($B_{\text{fus}}$) and at large values of impact parameter ‘$b$’, the projectile does not touch the target nucleus and is elastically scattered through the Coulomb field leading to the ‘distant collisions’. In such type of reactions, no mass is transferred from the projectile to the target nucleus and/or vice-versa, and the Coulomb forces exclusively determine the process (elastic scattering and/or Coulomb excitation). However, when

![Diagram showing different types of collisions](image)

**Figure 1.1: Distant, Grazing and close collisions in the classical picture of HI reactions.**

the projectile and target nuclei come into close contact then the nuclear interactions set in. Meaning thereby, if the impact parameter is comparable to the sum of the radii of the interacting partners, ‘grazing collisions’ may takes place and the projectile can be elastically or in-elastically scattered. As such, the projectile smoothly grazes along the outer surface of the target nucleus. Moreover, when the projectile interacts with the target nucleus at smaller values of impact parameter with relatively high bombarding energies (just enough to enter in the nuclear field range of target nucleus)
then ‘deep inelastic collisions’ (DIC) dominate. Here, the projectile interacts strongly with the target nucleus. In this region the overlap of the ions is much less than in case of fusion, but it is sufficient to allow a strong interaction between the two ions which transforms a sizeable fraction of kinetic energy into internal excitation energy of two reaction products. In such a case, the nuclear density rises very rapidly in the surface region of target nucleus, and a few nucleons may get transferred from the projectile to the target nucleus, which is also referred to as the ‘massive transfer reaction’. Further, if the projectile interacts with the target nucleus very strongly at still smaller values of impact parameters, the projectile completely fuses with the target nucleus resulting into the formation of a composite nucleus which undergoes statistical equilibrium.

The typical ranges of impact parameters that may lead to different processes are summarized in Table.1.1. The total cross-section may be related to the $l$-values according to the relation;

$$\sigma = \pi \lambda^2 l^2$$

(1.1)

where, $\lambda$ is the reduced wave-length of the incident ions. The Fig 1.2, shows the contribution of various $l$-values towards the total cross-section. In this figure, the values $l_{\text{crit}}$, $l_f$, $l_D$ and $l_{\text{max}}$ represent the limits of the angular momenta for the compound nucleus (CN) formation, fission-like (FL) phenomena, deep inelastic scattering (D) and quasi elastic (QE) reactions respectively. However, the relatively higher $l$-values contribute towards elastic (EL) scattering and Coulomb excitation (CE). The slanting long dashed line represents the geometrical partial cross-section and may be given by expression,

$$\frac{d\sigma}{dl} = 2\pi \lambda^2 l$$

(1.2)

Vertical dashed lines indicate the extensions of various $l$-windows in a sharp cutoff model with the characteristics $l$-values noted at the abscissa. Unshaded areas represent the diffused $l$-windows assumed in a smooth cutoff model [4].

At present, it is not clear, how large the overlapping regions are for an individual mode of reaction. In the simplest form, one can set an assumption of effect-
Table 1.1: Values of distance of closest approach (impact parameter) and angular momentum ($l$) representing different types of heavy-ion reactions

<table>
<thead>
<tr>
<th>Distance of closest approach ($r_{\text{min}}$)</th>
<th>Angular Momentum ($l$)</th>
<th>Type of Nuclear reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$ or $r_{\text{min}} &gt; R_N (= R_1 + R_2)$</td>
<td>$l &gt; l_N$</td>
<td>Coulomb excitation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Rutherford (elastic) scattering)</td>
</tr>
<tr>
<td>$R_F &lt; r_{\text{min}} \leq R_{\text{DIC}}$</td>
<td>$l_{\text{DIC}} &gt; l &gt; l_N$</td>
<td>Close collision</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Deep in-elastic scattering)</td>
</tr>
<tr>
<td>$R_{\text{DIC}} &lt; r_{\text{min}} \leq R_N$</td>
<td>$l_N &gt; l &gt; l_{\text{DIC}}$</td>
<td>Transfer reactions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(elastic and in-elastic scattering)</td>
</tr>
<tr>
<td>$0 \leq r_{\text{min}} \leq R_F$</td>
<td>$l &lt; l_F$</td>
<td>Fusion reaction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Compound nucleus formation)</td>
</tr>
</tbody>
</table>

Here, $r_{\text{min}}$ is the distance of closest approach, $R_N$ is the grazing range of nuclear force, $R_{\text{DIC}}$ is the minimum distance for the deep inelastic collision, while $R_F$ is the minimum distance for fusion reactions.

Figure 1.2: Schematic illustration of the reaction probability as a function of entrance channel angular momentum ($l$).
-ive nuclear potential $V_{\text{eff}}$, that depends on the relative separation ($r$) of two interacting nuclei. The $V_{\text{eff}}$, as a function of ‘$r$’ and relative angular momenta ‘$l$’ may be written as the sum of Coulomb, nuclear and centrifugal potential terms and may be given as,

$$V_{\text{eff}} (r,l) = V_{\text{Coul}} (r) + V_{\text{nuc}} (r) + V_{\text{cent}} (r,l) \quad (1.3)$$

where, $V_{\text{Coul}}(r)$ is the Coulomb potential, $V_{\text{nuc}}(r)$ is the nuclear potential and $V_{\text{cent}}(r, l)$ is the centrifugal potential.

The repulsive Coulomb potential $V_{\text{Coul}}(r)$ may be given as,

$$V_{\text{Coul}} (r) = \frac{Z_1 Z_2 e^2}{4 \pi \varepsilon_0 r}; \text{ for } r \geq (R_1 + R_2) \quad (1.4)$$

and

$$V_{\text{Coul}} (r) = \frac{Z_1 Z_2 e^2}{4 \pi \varepsilon_0 r} \left( 3 - \frac{r^2}{R_{\text{Coul}}^2} \right); \text{ for } r \leq (R_1 + R_2) \quad (1.5)$$

Here, $Z_1$ and $Z_2$ are the atomic numbers, while, $R_1$ and $R_2$ are the radii of the projectile and the target nuclei, respectively. The complex short-range attractive nuclear potential $V_{\text{nuc}}(r)$ has been described in different forms. Wood-Saxon form is the simplest form for the nuclear potentials and is given as;

$$V_{\text{nuc}} (r) = \frac{V_0}{1 + \exp \left( \frac{r - R}{a} \right)} \quad (1.6)$$

where, $R= r_o \left( A_1^{1/3} + A_2^{1/3} \right)$, $V_0$ is the depth of the potential and ‘$a$’ is the diffuseness parameter.

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

$$V_{\text{cent}} (r,l) = \frac{\hbar^2}{2\mu} \frac{l (l+1)}{r^2} \quad (1.7)$$

here, $l$ is the angular momentum and $\mu$ the reduced mass of the interacting nuclei. The effective potential $V_{\text{eff}}(r, l)$ can be written as;
\[ V_{\text{eff}}(r, l) = \frac{Z_{1}Z_{2}e^{2}}{4\pi \epsilon_{0}r} + \frac{V_{o}}{1 + \exp \left( \frac{r-R}{a} \right)} + \frac{l(l+1)}{2\mu r^{2}}; \text{ for } r \geq (R_{1} + R_{2}) \]  

where, the terms used have their usual meanings. It may be observed that the magnitude of \( \mu r^{2} \) strongly affects the contribution of the centrifugal potential to the effective interaction potential for each partial wave. As a representative case, the effective potential \( V_{\text{eff}}(r, l) \) for \(^{16}\text{O} + ^{181}\text{Ta} \) system, as a function of relative separation \( r \) between interacting ions is shown in Fig.1.3, for different \( l \)-values. In this figure \( 'r' \) is the distance of closest approach which is related to the impact parameter \( 'b' \) by the relation \([5]\),

\[ r = \frac{b}{\sqrt{1 - \frac{V(r)}{E_{\text{cm}}}}} \]  

Its relation to the interaction radius \( 'R_{\text{int}}' \) determines the characteristics of the reaction which are described on the right panel of the Fig. 1.4.

The heavy-ion collisions with \( r > R_{\text{int}} \) do not lead to nuclear interactions. In case of such collisions, Coulomb excitation and elastic scattering are the only phenomena which yield the scattered projectile and target in exit channel. For somewhat smaller angular momenta \( l \) associated with \( r \) values of the order of interaction radius \( (r \geq R_{\text{int}}) \), inelastic scattering and exchange of few nucleons are induced in peripheral or grazing like collisions. Consequently there is some loss of kinetic energy of relative motion. For smaller \( l \)-values, with \( r < R_{\text{int}} \), the interacting nuclei come into contact. A window opens between reaction partners along with a considerable exchange of mass and damping of the relative kinetic energy. Such damped interactions may produce more than two heavy fragments in the exit channel. For \( r < < R_{\text{int}} \) deeply penetrating fusion-fission like collision occurs where the window between the reaction partners becomes so large that a single nucleus with a continuous interior is produced. Apart from the above discussed reactions, if the excitation energy of the composite system is quite high, the process of fission may also be a dominant mode of interaction.
**Figure 1.3:** Plots of effective potential $V_{\text{eff}}(r, l)$ as a function of relative separation $r$, between the interacting ions for the system $^{16}\text{O} + ^{181}\text{Ta}$.

**Figure 1.4:** Schematic diagram of the classical scheme of collision between heavy nuclei.
1.3 FISSION

Nuclear fission is an extremely complex reaction. Fission can, in some heavy nuclei, occur spontaneously, or, in the excited nuclei produced in the nuclear reaction. In general, the energy released in a single fission reaction of a heavy nucleus amounts to around 200 MeV or so. This energy release is due to the increase in the binding energy of the fission fragments. In general, the binding of nuclei is governed by the competition of two forces. The electrostatic interaction acts repulsively between the protons, while it leaves the neutrons unaffected. The strong interaction acts primarily attractively, and it makes little difference between protons and neutrons, i.e., attraction can be present in all pair wise combinations of protons and neutrons. The strong interaction outperforms the electromagnetic interaction at typical distances between two nucleons in a nucleus (≈ 1 fm), and has a short range, which vanishes almost at a few fm. The electrostatic repulsion, on the other hand, is intrinsically weaker in magnitude, but has an infinite range and varies as $1/r$. As a consequence, nuclei in the mid-mass range are the most tightly bound. While in heavier nuclei, there is large repulsion between the protons, which increases as $Z^2$ and the heavy nucleus may split into fragments. The fragments can gain binding energy by splitting into two halves. The phenomenon of fission can be explained theoretically with the help of semi-empirical mass formula [6]. In Fig. 1.5, the potential energy during the

![Figure 1.5: Potential energy during the fission process vs. the deformation.](image)
The fission process is shown. The minimum in energy, where the nuclear ground state is located, appears at a moderate deformation of the nucleus. A further increased deformation, however, will not be fully compensated by Coulomb or structure effects, which results in an energy increase, and this is represented as the fission barrier \( B_f \). In order that the fission takes place, the nucleus has to overcome \( B_f \). When a certain degree of deformation (saddle point) has been reached, the Coulomb forces, striving to separate the protons and the attractive nuclear forces are equally strong. As the deformation slightly increases beyond this point, the Coulomb forces become dominant and the nucleus undergoes fission.

Experimentally it was observed that depending upon the excitation energy, angular momentum, mass asymmetry of the entrance channel etc., the composite system formed as a result of HI collision either forms an equilibrated compound nucleus or undergoes fission before equilibration. The damping of the incoming radial motion relaxes the excitation energy by inducing spinning of the composite system and also statistical evaporation of particles (mostly neutrons). The main features of the fusion-fission reactions of the compound nuclear fission were established. However, it became quite apparent in early nineties that considerable departures were possible and new reaction paths or mechanism were needed to explain anomalous properties in fission observables. As the total angular momentum \( J \) of the CN increases, fission barrier begins to drop and ultimately reaches to zero value where CN becomes unstable against spontaneous fission. Such prompt fission reactions are referred to as fast fission [7]. The angular distributions of the fragments have been found to be forward peaked and the mass distribution are extremely wide. However, some reports indicate that at energies, typically intermediate between Coulomb barrier and that required for the onset of the fast fission, the mass distribution of the fission fragments are found to be transforming to mass asymmetric. These processes were named as ‘quasi fission’ [8] as it is apparent that the systems are not proceeding along fusion-fission path and follow entirely different path. This gives an important information about the dynamics of the heavy ion induced fusion-fission reactions. Further, fission like events may also arise due to the partial linear momentum transfer (termed as incomplete fusion- fission (IFF) events) and/or by the full linear momentum transfer (termed as complete fusion- fission (CFF) events). In such heavy-
ion reactions, the excitation energy and angular momentum imparted in the system are relatively higher, as such the process of fission is also a dominant mode of reaction. The final reaction products i.e., fission-like events, may be produced by the direct fission (first chance fission) and/or after the emission of few nucleons (second, third, etc. chance fission) and characteristic γ-radiations from fission-like events [9]. As a representative case, schematic representations of CFF and IFF reactions in $^{16}\text{O}+^{181}\text{Ta}$ system are shown in Figs. 1.6 and 1.7, respectively. As can be seen from Fig. 1.6, that the composite system $^{197}\text{Ti}$ formed as a result of complete fusion (CF) of $^{16}\text{O}+^{181}\text{Ta}$ may undergo fission giving rise to the population of $^{71}\text{Zn}$ and $^{117}\text{Cd}$ residues leaving behind an $\alpha$-particle and few nucleons. However, the same heavy residues may also be populated if the incomplete fusion (ICF) of $^{12}\text{C}$ (if $^{16}\text{O}$ breaks up into $^{12}\text{C}+\alpha$) with $^{181}\text{Ta}$ forms a composite system $^{193}\text{Au}$ in excited state, which undergoes fission (see Fig. 1.7). A general pictorial representation of de-excitation of a composite nucleus by the emission of light nuclear particle(s), the characteristics γ- radiations and/or via fission, (depending on the available excitation energy and entrance channel mass

![Figure 1.6: Pictorial representation of complete fusion-fission (CFF).](image1)

![Figure 1.7: Pictorial representation of incomplete fusion-fission (IFF).](image2)
asymmetry), is shown in Fig. 1.8. In the present work, in order to have complete understanding of the processes involved in $^{16}\text{O} + ^{181}\text{Ta}$ interaction at $E_{\text{Lab}} \approx 6.5$ MeV/nucleon, a programme to study the dynamics of the processes in this system has been undertaken. In the first part of the work the experimental data on excitation functions for a large number of reactions in this system were analysed to study the complete and incomplete fusion processes in the energy range $\approx 76$-100 MeV [10].

![Diagram of fusion-fission process](image)

**Figure 1.8:** Pictorial representation of fusion-fission process passing successively through various stages.

Further, experiments were carried out to study the fractional momentum transfer involved in CF and/or ICF processes at several beam energies for the same system [11]. During the analysis of the data for this system it has been observed that several residues, which are not expected to be populated via CF and/or ICF processes, are also populated. These residues were found to have charge and atomic mass numbers around half of the CF and/or ICF residues indicating possibility of their production via fission of heavy composite system formed by CF and/or ICF. As such, the data has been further analysed within the frame work of fission to study the fission
fragment mass distribution at ≈ 97 and 100 MeV beam energy. In the present report a detailed analysis of the $^{16}\text{O}+^{181}\text{Ta}$ system has been presented [12, 13].

In the Chapter II of this dissertation, a detailed description of the pelletron accelerator and the technique used for the measurements along with the irradiation etc., are described. However, in the Chapter III, measurement of fission fragments, consisting of formulations used, identification of fission residues and relevant nuclear data etc., are presented. Further, the results of fusion-fission experiment for the $^{16}\text{O}+^{181}\text{Ta}$ system have been used to obtain mass as well as isotopic yield distributions of fission fragments and are described in the Chapter IV. Summary and conclusions are presented at the end.
References

Phys. Rev. C. (2011), accepted for publication
EPJ web of Conferences, published by EDP Sciences, 2011