Chapter 1

Nuclear reactions \textit{tool to probe the nucleus}

1.1 Preamble

The journey to understand the fundamental nature of the matter, which has always been the quest for human being, starts in particular from the 4\textsuperscript{th} century. At that time “Democritus” believed that each kind of material could be sub-divided into the “\textit{smallest indivisible element, invisible to the naked eye}”, called the “\textit{atom}” and theory was referred to as “\textit{atomism}”. The idea of atomism remained only a speculation, until investigators in the early 19\textsuperscript{th} century applied the methods of “\textit{experimental science}” to this problem and obtained the evidence needed to raise the idea of “\textit{atomism}” to the level of a full-fledged scientific theory. The journey got accelerated with the discovery of “\textit{radioactivity}” in 1896 by Becquerel *, while investigating phosphorescence in uranium salts, which led to the realization that the radioactive elements spontaneously got transmuted into other elements\cite{1}. The discovery was further verified with the identification of radio-activity in some materials by the Curies in 1898. J. J. Thomson \cite{2}, a year later, proposed a model of the atom known as “\textit{plum pudding model}” in which it is perceived that the atom is like a large positively charged ball with negatively charged electrons embedded inside it. The model could account for the stability of atoms, but could not account for the discrete wavelengths observed in the spectra of light emitted from excited atoms. The ‘\textit{existence of the nucleus as the tiny central part of an atom}’ was first proposed by

\footnote{The 1903 Nobel Prize in Physics was awarded jointly to Becquerel, for his discovery, and to Pierre & Marie Curie for their subsequent research into radioactivity.}
Chapter 1. Nuclear reactions

tool to probe the nucleus

Rutherford in 1911 [3], as a result of the interpretation of famous 1909 \(\alpha\)-scattering experiment, performed by Hans Geiger and Ernest Marsden in his guidance [4]. In order to explain the stability of atom and also to explain the emission spectra Niels Bohr, in 1913, gave the model [5], which is a quantum-physics-based modification of the Rutherford’s model, known as Bohr’s model \(^1\). Later, as a result of many scattering experiments it was established that matter is made up of atoms with the nucleus at their center and electrons as revolving around them in almost circular orbits. This tiny central core, called ‘nucleus’, is made up of nucleons, the protons and neutrons. Almost all the mass of an atom is located in the nucleus, with a very small contribution from the orbiting electrons.

From deuteron to uranium, there are almost 1700 nuclei that are found naturally on earth. In addition, a large number of others are created by transmutation in the laboratory and in the interior of stars. The first astounding work on ‘artificial transmutation’ of the nucleus was performed by Rutherford in 1919, using energetic \(\alpha\)-particles as projectile. In this direction a big boost was given in 1932, with the development of charge particle accelerator, by J. D. Cockcroft & E. T. S. Walton [6], the associates of Rutherford. 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 the strong attractive nuclear forces. Though, information on the exact nature of nuclear forces is still limited and not well established, however, much progress has been made towards its phenomenological understanding. Some of the basic aims of nuclear physics research are to improve our understanding regarding the nuclear structure, nuclear properties, nuclear forces, energy states of nuclei, transition probability, nature of interactions, decay characteristics of excited nuclei etc. More recently, the possibility of formation of the super heavy elements (SHE), considerably motivated the nuclear reaction studies[7, 8].

A large fraction of our knowledge on the properties of nuclei is derived

\(^1\)Niels Henrik David Bohr was a Danish physicist who made foundational contributions to the understanding atomic structure and quantum mechanics, for which he received the Nobel Prize in Physics in 1922.
1.1 Preamble

from the study of nuclear reactions. In general, a nuclear reaction takes place, when a particularly chosen nuclide (target nucleus) is bombarded by a projectile nucleus of sufficient kinetic energy, to overcome the fusion barrier \(V_{\text{fus}}\) between interacting partners. As a consequence of such an interaction, the projectile and target nuclei come close to each other within the range of nuclear forces, eventually transforming them into an excited composite system and then to the final stage, consisting of reaction products, like; light ejectile(s) and a residual nucleus followed by the emission of characteristic \(\gamma\)-radiations [9]. A typical nuclear reaction may be represented as;

\[
\frac{A_a}{Z_a}a + \frac{A_X}{Z_X}X \rightarrow \frac{A_Y}{Z_Y}Y + \frac{A_b}{Z_b}b + Q \quad (1.1)
\]

Here; \(\frac{A_a}{Z_a}a, \frac{A_X}{Z_X}X, \frac{A_Y}{Z_Y}Y\) and \(\frac{A_b}{Z_b}b\) are the projectile nucleus, target nucleus, the residual nucleus and the emitted particle, respectively. Where, \(Q\) is the energy balance of the reaction. During such a reaction the energy is either evolved or absorbed. The total amount of energy evolved or absorbed is called the “\(Q\)-value of the reaction”. The \(Q\)-value of the reaction may be written as;

\[
Q = (M_a + M_X) - (M_b + M_Y) = (E_b + E_Y) - (E_a + E_X) \quad (1.2)
\]

Where, \(M_a, M_X, E_a\) and \(E_X\) are the masses and energies of particles in the entrance channel; \(M_b, M_Y, E_b\) and \(E_Y\) are the masses and energies of particles in the exit channel in a binary reaction of the type \(X(a,b)Y\). On the basis of \(Q\)-value, the nuclear reactions may be categorized as; \((a)\) Exoergic reactions \((Q>0)\), in which energy is evolved, and \((b)\) Endoergic reactions \((Q<0)\), in which energy is absorbed. Since, there is a net deficit of energy in the later, therefore, energy must be supplied to initiate such a nuclear reaction, which usually comes from the kinetic energy \(E_a\) of the projectile. When the ejectile \(b\) is emitted in the forward direction, then the ‘threshold energy’ \(E_{\text{th}}\) in an endoergic reaction is given as;

\[
E_{\text{th}} \approx (1 + \frac{M_a}{M_X}) \cdot | - Q | \quad (1.3)
\]
The nuclear reactions may also be categorized as:

- ‘elastic reactions’, in which interacting partners only change their direction of motion. In this case, the particles in the exit channel are exactly same as that in the entrance channel, and

- ‘inelastic reactions’, where one or both of the interacting partners may change their internal states alongwith their nuclear properties.

In a nuclear reaction the properties of initial and final systems are well defined but it is not known what exactly happens during the time of projectile-target interaction, due to very short time $\approx 10^{-22} - 10^{-16}$ sec. In order to understand the mechanism of nuclear reactions, V. F. Weisskopf proposed a general scheme, based on the optical model approach, shown in Fig.1.1, by which the different stages of the reaction can be visualized.

![Diagram showing stages of a nuclear reaction](image.png)

Figure 1.1: Typical lay out of Weisskopf method to describe the nuclear reactions.
According to Weisskopf’s approach when a projectile is incident on a nucleus, it first feels the presence of the complex optical potential, known as the single particle stage. The real part of the optical potential is responsible for the shape elastic scattering, however, due to the imaginary part, a part of the incident wave is absorbed leading to the direct reactions and/or to the formation of compound nucleus. These two limiting reaction processes are differentiated by their interaction time duration; direct reactions last for as long as it takes the projectile to go through the target nucleus, which is typically of the order of $10^{-22}$ sec. However, in the compound nucleus reactions the sharing of the projectile’s energy and momentum among the nucleons of the target nucleus takes place and a thermodynamic equilibrium is established. The time scale for such reactions is typically $\approx 10^{-16}$ sec. In between, there is a region known as the pre-equilibrium stage, in which a limited number of collisions with the nucleons may take place before the establishment of equilibrium, and is intermediate in time scales.

Another approach to explain the nuclear reaction dynamics is based on the ‘compound nucleus (CN) theory’, proposed by Bohr in 1936 [5]. According to CN theory, the energetic projectile ($E \geq V_{fus}$; where $V_{fus}$ is the fusion barrier) is captured by the target nucleus forming an excited composite system. The total kinetic energy and driving input angular momenta of the projectile are equally shared among all the constituent nucleons of the composite system leading to the establishment of thermodynamic equilibrium, of the ‘compound nucleus’. The CN so formed is in the excited state and is inherently an unstable system. After a long time ($\approx 10^{-16}$ sec), when a very large number of collisions have taken place, sufficient amount of energy may be accumulated on a nucleon or on a group of nucleons to be ejected from the CN, leaving behind a residual nucleus. Since, the CN is relatively a longer lived entity, Bohr assumed that the nuclear reaction proceeds in two steps, viz; (i) formation of the CN, and (ii) the decay of the CN. Further, the decay of the CN is assumed to be independent of the mode of its formation and thus known 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 [5]. The validity of ‘Bohr’s independent hypothesis’ was experimentally verified by
S. N. Ghoshal in 1950 [10], where the reaction cross-sections for particular reaction products, formed via de-excitation of the same CN formed through different entrance channels, have been found to be almost the same orders of magnitude within the experimental uncertainties. The CN reactions are found to be valid at relatively low energies, and remain a fruitful source of information about nuclear structure and its properties.

On the other hand, in the direct reaction mechanism, it is assumed that only a nucleon, or a cluster of nucleons, in the projectile interacts with one of the nucleons, or a cluster, in the target nucleus without exciting the internal degrees of freedom in any of the clusters or the rest of the nucleus. The basis for taking such a direct reaction point of view is the short interaction time $\approx 10^{-22}$ sec. The direct reactions may, further, be classified into two categories viz; (i) knock-out, and (ii) stripping/pick-up reactions. In the knock-out reactions, a nucleon of the target nucleus may be knocked out by the energetic projectile. In case of stripping reactions, the target strips a nucleon (or a group of nucleons) from the projectile, and remaining part of the projectile may continue to move on, more or less undisturbed. The inverse of the stripping reaction would be a pick-up reaction; in which the projectile pick(s) up nucleon(s) from the target nucleus. Direct reactions are likely to occur at relatively large projectile energies.

With the availability of accelerated charged particle beams, the growth from the Cockroft and Walton’s machine to today’s Large Hadron Collider (LHC), and the huge development in the detection techniques & high speed computation facilities, has resulted in several new branches of nuclear physics research. There are three broad categories of the study of nuclear reactions based on the energy regions of interest; (i) Low Energy Nuclear Reactions, (ii) Medium Energy Nuclear Reactions, and (iii) High Energy Nuclear Reactions. The present thesis deals with some of the interesting problems associated with low energy heavy-ion (HI) induced nuclear reactions, which has been a topic of resurgence interest for HI nuclear physics community since last decade or so. In the next sections some of the important features of HI-induced reactions have been dicussed in brief.
1.2 Heavy-ion induced reactions

The heavy-ion (HI) collisions deal with the phenomena that occur when two nuclei (heavier than α-particle) are brought in contact with each other within the range of nuclear forces. Various heavy nuclei that exist in nature, particularly, never come in contact with each other at the temperatures that occur in nature, the only exception being reactions produced by cosmic rays. In recent years, particle accelerators have been constructed, which are capable to accelerate nuclei and provide an opportunity to study and understand various properties of nuclei. Hence, much interest has aroused to study the reaction mechanism in HI-interactions during the last decade or so. In general, when two nuclei are brought in contact, a variety of phenomena can occur. By appropriately selecting the target, the projectile and the incident energy it is possible to excite different degrees of freedom. Since, the HI-interactions deal with relatively large mass, the associated de-Broglie wavelength ($\lambda$) in HI-induced reactions is very small, typically of the order of nuclear dimensions and can be expressed as:

$$\lambda = \frac{1}{2\pi} \frac{h}{\sqrt{2mE_{lab}}}$$  \hspace{1cm} (1.4)

Since, the de-Broglie wavelength ($\lambda$) of the heavy-ions is very small, therefore, the HI-induced reactions can be described using semi-classical approach. In this approach, one considers the radial motion of ions classically and angular motion in central force field quantum mechanically. The semi-classical nature of HI-induced reactions makes it possible to give general description of their classical characteristics, particularly, their relative motion along well defined orbits in terms of the distance of closest approach between interacting nuclei ($r_{min}$), which is related to the impact parameter $b$, as:

$$r_{min} = \frac{b}{\sqrt{1 - \frac{V(r_{min})}{E_{CM}}}}$$  \hspace{1cm} (1.5)
where, $V(r_{\text{min}})$ is the nuclear potential between the two interacting nuclei and $E_{\text{CM}}$ is the center of mass energy. The classical trajectories of projectile leading to the different reactions may be classified on the basis of impact parameter, as schematically represented in Fig. 1.2.

![Figure 1.2: Classical view of heavy ion interactions, showing different trajectories.](image)

As can be seen from this figure, at projectile energies deep below the fusion barrier ($V_{\text{ fus}}$) (i.e., at large values of impact parameters), the nuclear interaction is negligible and projectile may be elastically scattered, leading to the ‘distant collisions’ i.e., elastic scattering and Coulomb excitation processes. If the impact parameter is comparable to the sum of the radii of the interacting partners, ‘grazing collisions’ may take place and the projectile can be elastically or inelastically scattered. In this process, the system keeps its original asymmetry in kinetic energy, mass, etc. When the projectile interacts with the target nucleus at relatively smaller values of impact parameters with relatively high bombarding energies (just enough to enter in the nuclear force field of target nucleus; peripheral collisions)
then ‘deep inelastic collisions’ (DIC) dominate, in which the projectile interacts strongly with the target nucleus. In such a case, the overlap of the ions is relatively less than in the case of fusion, and the nuclear densities rise very rapidly in the surface region and form a dinuclear system which lasts for some time. The two parts are connected to each other with a neck, through which a substantial part of the energy is transferred, and a few nucleons may get transferred from the projectile to the target nucleus. In this impact parameter window, another important process sets in i.e., the break-up fusion or the in-complete fusion reactions, in which the projectile breaks up into parts, one of which is assumed to fuse with the target nucleus, while the other flies away almost undisturbed. These are also referred to as ‘massive transfer reactions’. Further, if the projectile interacts with the target nucleus very strongly at smaller values of impact parameters (central collisions), it predominantly leads to the formation of a composite nucleus, in which a large part of excitation energy is in the form of an orderly collective translational motion of the nucleons, which is transformed into chaotic thermal motion through nucleon-nucleon interactions. The thermalization eventually leads to a compound nucleus (CN), which decays through usual modes of de-excitation. The ranges of impact parameters associated with different processes are summarized in Table.1.1.

Table 1.1: The ranges of impact parameter and angular momentum associated, with different types of heavy-ion interactions

<table>
<thead>
<tr>
<th>Impact parameter ( (b) ) ( b &gt; R_N = (R_1 + R_2) )</th>
<th>Angular momentum ( (\ell) ) ( \ell &gt; \ell_N )</th>
<th>Types of interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rutherford scattering or Coulomb excitation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inelastic scattering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transfer reactions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep inelastic scattering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fusion (CN formation)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chapter 1. Nuclear reactions tool to probe the nucleus

(Where, $R_N = R_1 + R_2$, is the sum of radii of interacting partners, and $b$ is the corresponding impact parameter.)

In HI-induced reactions, after surpassing the fusion barrier, the interacting partners may lose some of the energy through nuclear friction to get trapped in the pocket of the effective potential, forming a compound nucleus. In general, the angular momentum dependent partial reaction cross-section $\sigma^R(E)$, at a given bombarding energy may be given as;

$$\sigma^R(E) = \pi \lambda^2 (2\ell + 1) T_\ell(E) \quad (1.6)$$

where, $T_\ell(E)$ is the transmission coefficient for a particular $\ell$-wave.

In the simplest form, one may assume a nuclear potential which depends on the relative separation ‘$r$’ of two interacting nuclei. The nucleon-nucleon interaction is the key for the proper understanding of any nuclear phenomenon. In nuclear reactions, emphasis is laid on the interaction between incident particle and the target nucleus. The nuclear scattering processes are more sensitive to the effective potential $V_{eff}(r)$ in the nuclear surface region. The $V_{eff}(r)$ as a function of distance and relative angular momenta consists of the sum of nuclear, Coulomb and centrifugal potential terms and may be given as,

$$V_{eff}(r) = V_{nucl}(r) + V_{Coul}(r) + V_{cent}(r) \quad (1.7)$$

where; $V_{nucl}(r)$ is the attractive nuclear potential, however, $V_{Coul}(r)$ and $V_{cent}(r)$ are the Coulomb and centrifugal potentials, respectively, which are both repulsive in nature. There are several approaches to represent the complex short range attractive nuclear potential $V_{nucl}(r)$. The most commonly used form of the nuclear potential is the Woods-Saxon form, which may be given as;

$$V_{nucl}(r) = \frac{V_0}{1 + exp(\frac{r-R}{a})} \quad (1.8)$$
Where, \( R = r_0(\frac{A_1^{1/3} + A_P^{1/3}}{3}) \), \( V_0 \) is the depth of the potential, ‘\( a \)’ the diffuseness parameter and \( r_0 \) is generally taken as 1.31 \( fm \).

The repulsive Coulomb potential \( V_{\text{Coul}}(r) \) may be expressed as follows;

\[
V_{\text{Coul}}(r) = \frac{1}{4\pi \varepsilon_0} \frac{Z_P Z_T e^2}{r}, \quad \text{for} \quad r\geq (R_P + R_T)
\]

(1.9)

Here, \( Z_P \) and \( Z_T \) are the atomic numbers, while \( R_P \) and \( R_T \) are the radius of the projectile and the target nuclei, respectively.

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

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

(1.10)

Here; \( \ell \) is the angular momentum and \( \mu \) is the reduced mass of the interacting partners. As a representative case, the effective potential \( V_{\text{eff}}(r) \) for \( ^{12}\text{C} + ^{159}\text{Tb} \) system as a function of relative separation \( (r) \) between interacting ions is shown in Fig.1.3, for different \( \ell \)-values. The dependence of the reaction probability, for different types of collisions, on the impact parameter ‘\( b \)’, can be converted into a dependence on the input angular momenta, using the relation;

\[
\vec{\ell} = \vec{p} \times \vec{b} = m_p \cdot \vec{v}_p \times \vec{b}
\]

(1.11)

In this expression \( m_p \cdot \vec{v}_p \) denotes the asymptotic initial momentum of the projectile nucleus relative to the target nucleus.

The different processes dominate in different \( \ell \)-windows and thus the reaction cross-section in different regions may be written as;

\[
\sigma_{\ell_i} = \pi \lambda^2 \sum_{\ell_i}^{\ell_{i+1}} (2\ell + 1) \times T_{\ell}
\]

(1.12)
where, \(i=1,2,...\) correspond, respectively, to fusion, deep in-elastic and/or break-up fusion, peripheral collisions, and to Coulomb-excitations. A qualitative picture of the reaction probability (\(\sigma_\ell\)) as a function of entrance channel angular momentum (\(\ell\)) is given in Fig.1.4, for the collision types discussed above.

Figure 1.3: Plots of effective potential \(V_{eff}(r)\) as a function of relative separation (\(r\)) between the interacting ions for \(^{12}\text{C}^{+}{^{159}\text{Tb}}\) system.
As can be observed from Fig.1.4, the area below the dotted segments give the reaction cross-section for CN formation ($\sigma_{CN}$), deep inelastic collision ($\sigma_{DIC}$), direct reactions ($\sigma_D$) to the elastic collisions and/or Coulomb excitation ($\sigma_{EL+CE}$).

As indicated in this figure, different regions are overlapping in different $\ell$-values. At present, it is not clear, how large the overlapping regions are for a individual mode of reaction. Further, it is now well established that, in HI-induced reactions at energies near and above the $V_{fus}$, some of the most dominant processes are; (i) complete, (ii) in-complete fusion and (iii) pre-equilibrium emission. Brief description of these processes is given in the following sub-sections;

1.2.1 Complete fusion (CF) reactions

In the complete fusion (CF) reaction, a composite system is formed after an intimate contact and transient amalgamation of interacting nuclei leading
to the formation of an excited composite system. After the equilibration of this system a "compound nucleus" is formed, which may decay through the emission of particles and/or $\gamma$-radiations depending upon the available excitation energy. For the CN formation to take place;

- the energy of the projectile must be sufficient enough to overcome the Coulomb barrier;
- the projectile and the target nucleus should have sufficient mass overlap for amalgamation to occur;
- the entrance channel input angular momenta ($\ell$) should not exceed the maximum angular momenta that the composite system can sustain.

As mentioned above, the CF reactions are said to occur at central and/or near central impact parameters and for the input angular momenta range $0 \leq \ell \leq \ell_{\text{crit}}$, where the probability of CF is expected to be maximum. The $\ell_{\text{crit}}$ is the upper limit of sustainable input angular momentum by CN [11, 12]. In such a case, the attractive nuclear potential overcomes the sum of repulsive Coulomb and centrifugal potentials. Consequently, the target nucleus hugs the entire projectile with the involvement of all nucleonic degrees of freedom essentially at the projectile energies comparable to the $V_{\text{fus}}$ or well above it. After the fusion of projectile and the target nucleus, they lose their previous collective and individual characteristics, and thus form a new single nuclear system, which finally leads to the formation of equilibrated compound nucleus. A typical representation of complete fusion reactions is given in Fig.1.5. Some of the signatures of the CF-reactions are given below;

- Full amalgamation of the projectile and the target nuclei occur for $\ell \leq \ell_{\text{crit}}$.
- The mass number and the charge of the composite system is equal to the sum of the mass number and charge of the projectile and the target nuclei. The composite system has pre-determined excitation energy, angular momentum, etc.
1.2 Heavy-ion induced reactions

- Total linear momentum of the projectile is transferred to the composite system and, hence the CF residues recoil at angles very close to the beam direction.

- The measured excitation functions are satisfactorily reproduced by the statistical model calculations.

- Spin distribution of the residues formed via CF reactions is found to increase monotonically towards the band head.

It has been experimentally observed that the total CF cross-section \( \sigma_{CF} \) is smaller than the total reaction cross-section \( \sigma_R \) at a given projectile energy.

![Figure 1.5: A typical representation of CF reaction dynamics: formation and decay of compound nucleus.](image)
As a matter of fact, large angular momenta inhibit the CF, which is expressed as the $\ell$ cut-off for CF ($\ell_{\text{crit}}$), above which the centrifugal potential is so large that it prevents fusion between two colliding nuclei. Starting with usual expression (equation-1.7), the sharp-cut-off model may be used to calculate the cross-section for CF as a summation of contributing $\ell$-values from $\ell=0$ upto a limiting value $\ell=\ell_{\text{crit}}$, where the probability of CN formation is assumed to be maximum. Since, $\ell$-values are related to the interaction trajectories, therefore, at higher $\ell$-values beyond $\ell_{\text{crit}}$ or at relatively higher values of impact parameters, minimum mass overlap between projectile and target nuclei takes place, thus entering in the regime of break-up-fusion reactions.

### 1.2.2 In-complete fusion (ICF) reactions

In these reactions, a part of the projectile is assumed to fuse with the target nucleus, while remnant flows in the forward direction without interaction with target nucleus. The concept of such in-complete mass transfer in HI-reactions has originated after the pioneering experimental observation of fast-$\alpha$-particles by Britt and Quinton [13] at higher energies $> 10.5$ MeV/A. A ‘hot’ incompletely fused composite (IFC) system is formed, in case of in-complete fusion (ICF) reactions. In such a case, relatively less nucleonic degrees of freedom are expected to be involved compared to CF. A typical representation of ICF reaction dynamics is given in Fig.1.6. It may be mentioned that, for peripheral collisions (at relatively higher $\ell$-values) and/or at higher projectile energies the ICF starts competing with CF, where the centrifugal potential ($V_{\text{cent}}$) becomes relatively higher. As can be seen from Fig.1.4, for higher $\ell$-values the attractive fusion pocket vanishes in the effective potential energy curve. As such, the nuclear potential is no more strong enough to capture the entire projectile to form the composite system. It may be seen from Fig.1.4, that at $\ell \leq \ell_{\text{crit}}$, a pocket remains in the potential energy curve, however, the pocket disappears for higher values of $\ell > \ell_{\text{crit}}$ (depends on projectile energy and impact parameter). As such, for $\ell \geq \ell_{\text{crit}}$ no fusion can happen unless a part of the projectile is emitted as a spectator ($P^*$) to provide sustainable input angular momentum [11, 12].
After such an emission, the remnant (participant: $P^p$) is supposed to have input angular momenta less than or equal to its own critical limit for fusion ($\ell_{\text{eff}} \leq \ell_{\text{eff}}^{P^p+T}$). After $\alpha$-particle emission the potential curve is obtained for a lower $\ell_{\text{eff}}^{P^p+T}$-value, where the pocket exists, as shown in Fig. 1.4. Hence, an excited IFC system ($P^p + T$) is formed with less mass/charge and excitation energy as compared to that formed in CF reactions. This excited composite system then decays via particle and/or $\gamma$-emission.

![Figure 1.6: A typical representation of ICF reaction dynamics](image)

In case of ICF reactions either $\alpha$-particles or clusters of $\alpha$-particles (as spectator) have, generally, been observed. As has already been discussed, the ICF reactions are likely to set in for $\ell > \ell_{\text{crit}}$. However, it has experimentally been observed that there is no such boundary of input angular momentum demarcating the CF and ICF reactions. Both the processes are
found to contribute significantly below and/or above their input angular momentum limits. Some of the prominent features of ICF reactions, which have emerged from a qualitative inspection of experimental results are summarized below;

- The fused composite system is formed with less mass and charge as compared to the total mass and charge of interacting partners [14].

- The forward recoil velocity of the reaction products formed via ICF has been found to be less than those populated via CF [15].

- The angular distribution of outgoing projectile-like fragments is found to be peaking at forward angles, where the $\alpha$-particle(s) are emitted with a velocity centered nearly equal to the projectile velocity [16, 17].

- The ICF processes mainly occur for the $\ell$-values above the $\ell_{crit}$ for CF [11, 12].

- The spin-distribution and side-feeding intensity pattern of residues formed via ICF are found to have distinctly different trends than those formed via CF [18].

The additional break-up degrees of freedom make the fusion process more complicated and the possible reaction processes may be: i) the non-capture break-up (NCBU), when none of the breakup fragments is captured, ii) incomplete fusion (ICF), when one of the breakup fragments is captured, iii) sequential complete fusion (SCF), the successive capture of all the fragments by the target nucleus, and iv) the direct complete fusion (DCF), i.e., the capture of the projectile as a whole. Experimentally, it is not possible to disentangle the cross-section of direct ($\sigma_{CF}^D$) and sequential ($\sigma_{CF}^S$) complete fusion processes, because both the channels reach to the same final reaction residues. Hence, the complete fusion cross-section ($\sigma_{CF}$) is taken as the sum of $\sigma_{CF}^D$ and $\sigma_{CF}^S$. Further, the sum of $\sigma_{CF}$ and in-complete fusion cross-section ($\sigma_{ICF}$) may be referred to as the total fusion cross-section.
1.2.3 Pre-equilibrium (PEQ) reactions

Apart from the CF and ICF reaction processes, the pre-equilibrium (PEQ)-emission reactions are also important in the HI-interactions [19, 20]. After the interaction of the projectile with the target nucleus, one or more particles may be emitted, the energy is carried away by only one or a few nucleons. It is possible that the particle emission takes place after the first interaction, but well before the attainment of thermal equilibrium of the compound system. These processes are referred to as the “pre-equilibrium” or “pre-compound reactions”. Evidence for such reactions is provided by:

- the larger number of high energy light nuclear particles (LNPs) like neutrons and protons in the exit channel than expected from equilibrium decay;
- the forward peaked angular distribution of LNPs;
- the slowly descending tails of the excitation functions (EFs), etc.

The projectile-target interaction may be considered to take place via a series of stages corresponding to the successive nucleon-nucleon interactions. These stages are characterised by the number of excited particle-hole pairs, called the ‘exciton number’. At each stage it is possible for the particles to be emitted from the nucleus and these are the ‘pre-equilibrium particles’. The probability of emission of such pre-equilibrium particles decreases from stage to stage as the available energy gets evenly distributed through the nucleons of the CN. The CN then reaches statistical equilibrium and emits particles until this is no longer possible energetically, and finally goes to the ground state by $\beta$ and/or $\gamma$-emission. Zagrebaev and Penionzhkevich [22] have reviewed this field, covering some aspects of light particle emission in nucleus-nucleus collisions over a range of energies. At low incident energies there is insufficient energy for pre-equilibrium emission to occur, and it becomes progressively more likely as the incident energy increases.
1.3 Motivation a few questions in mind

Recently [23, 24, 25, 27], much interest has aroused to study the influence of incomplete fusion (ICF) on complete fusion (CF) as well as on the total fusion, in HI-interactions in the energy regime ≈ 4-7 MeV/A. Kauffmann and Wolfgang [28] in 1961 while studying the $^{12}$C+$^{nat}$Rh interactions at ≈ 7-10 MeV/A, observed strongly forward peaked angular distribution of various light nuclear particles. In the same year, Britt and Quinton [13] found similar observations in the reaction $^{16}$O+$^{nat}$Bi at energies ≥ 10 MeV/A. Later, Galin et al. [29], termed these reactions as the incomplete fusion reactions.

The advances in the study of ICF reaction dynamics took place after the spin distribution studies by Inamura et. al. [30, 31], using particle-$\gamma$-coincidence technique for the identification of CF and ICF channels. In order to explain the ICF reactions several approaches viz; SUMRULE model[32], Break-Up Fusion (BUF) model[33], Promptly Emitted Particles (PEP’s) model[34], Exciton model[19], HOT SPOT model[21], etc., have been proposed. Moreover, the leading-particle model of Natowitz et al.[35], Hybrid model of Blann et al.[20], Fermi-jet model[36], and Moving-Source model[37] have also been put forward and seem to explain some of the experimental data related to ICF at relatively higher projectile energies. As a matter of fact, the above existing models qualitatively explain the experimental data particularly at E/A ≥ 10.5 MeV, however, none of these models is able to provide satisfactory reproduction of the ICF data at lower incident energies ≈4-7 MeV/A, which triggered a resurgent interest to study the underlying reaction dynamics. Since, at present there is no theoretical model, which may explain the ICF data at low energies, there is a need to have more and precise data to understand the reaction mechanism and also for the theoretical development in the field.

In addition to this, the dependence of ICF on the projectile structure, energy, driving angular momentum ($\ell$), binding energy and/or alpha Q-value ($Q_{\alpha}$), mass-asymmetry [$\mu_A=A_T/(A_T+A_P)$], deformation of interacting partners etc., is also required to be explored to develop some kind of systematics. Several contradicting dependences of the fraction of in-complete fusion $F_{ICF}$ have been discussed in some recent reports [23, 25, 26, 27]. The
F\textsubscript{ICF} is a measure of the relative strength of ICF to the total fusion. In ref. [25, 26] it has been shown that the F\textsubscript{ICF} is independent of the target charge (Z\textsubscript{T}) and thus from the product of Z\textsubscript{P}·Z\textsubscript{T}. However, in ref.[27] of the same group, the fusion suppression is predicted almost proportional to the charge (Z\textsubscript{T}) of the target nucleus. In a recent paper by Gomes et al., [38] a trend of systematic behavior of the variation of F\textsubscript{ICF} as a function of the Z\textsubscript{T} is discussed. Further, Morgenstern et al., [39, 40, 41] presented the F\textsubscript{ICF} dependence on the mass-asymmetry ($\mu_A$). However, a recent paper [23], supplements the Morgenstern’s mass-asymmetry systematics by introducing the importance of projectile structure in addition to the mass-asymmetry ($\mu_A$) of the interacting partners.

It is pertinent to mention that most of the experiments to study the ICF processes have been carried out using mostly the $\alpha$-cluster beams viz., $^{12}$C, $^{16}$O and $^{20}$Ne. However, studies using non-alpha cluster beams are limited. To understand the effect of projectile structure on ICF, a series of experiments are planned using $^{13}$C, $^{14}$N and $^{18}$O beams on different targets. The experiments will provide a rich data set to understand the effect of entrance channel parameters on ICF processes. As a first step the excitation functions for several reaction products in $^{12}$C+$^{159}$Tb and $^{13}$C+$^{159}$Tb systems have been measured and are compared. For the first time, data for six systems $^{12}$C+$^{159}$Tb, $^{13}$C+$^{159}$Tb, $^{16}$O+$^{159}$Tb, $^{12}$C+$^{181}$Ta, $^{13}$C+$^{181}$Ta and $^{16}$O+$^{181}$Ta at the above-barrier energies have also been used to study the correlation between the ICF fraction and the alpha-Q-value of the projectiles. This comparison also allows us to study convincingly the effect of projectile on the underlying reaction dynamics.

Another important aspect of the HI-interactions is that of PEQ-emission reactions. Several experimental and theoretical studies indicate the existence of PEQ-emission at moderate excitation energies [42, 43, 44]. In order to have insight into PEQ-emission, a variety of dynamical models viz; Inter-Nuclear Cascade (INC) model [49, 50], the quasi-free scattering model (QFS) [51], HYBRID model [52], EXCITON model [53, 54, 55, 56], etc., have been proposed to explain the experimental data related to PEQ-emission. Generally speaking, these models have been used to describe the experimental
data obtained for light ion (LI)-induced reactions\textsuperscript{1}[57, 58]. The experimental data on PEQ-emission using heavy ion (HI)-beams is still limited to a few projectile target combinations only [59, 60]. It may be pointed out that the distinction of PEQ and EQ-emission is relatively difficult in case of HI-induced reactions than LI-induced reactions due to rather large angular momenta carried in by the HI-beams, and also due to the presence of incomplete fusion [23, 24] processes as well. In the HI-induced reactions, the emission of particles is expected to be originated from both the complete as well as in-complete fusion reactions. The PEQ-reactions in HI-reactions is important for a better understanding of the reaction dynamics. Apart from the above, the data on PEQ-emission for various projectile-target combinations may provide a data base for the recently proposed Accelerator Driven Sub-critical-reactor System (ADSS) [61]. Nonetheless, a rich data set on different modes of reactions may be useful not only to determine the optimum irradiation conditions to produce medically important radio-nuclides but also for the development of nuclear reaction models. This has lead to a renewed interest to the study of nuclear reactions.

1.3.1 Overview of the present work

In the present work, in order to explore some of the important issues related to the HI-reaction dynamics at energies near and just above the barrier, several experiments have been performed at the Inter University Accelerator Center (IUAC), New Delhi. In the present thesis the complete, in-complete and pre-equilibrium reactions have been studied with the help of following measurements;

- Excitation functions (EFs): as the preliminary indication of ICF reaction dynamics. Here, the relative contributions of CF and ICF processes have also been deduced for \(^{12}\text{C}+^{159}\text{Tb}\) and \(^{13}\text{C}+^{159}\text{Tb}\) systems in the energy range \(\approx 4-7\) MeV/A, and found to be sensitive to the various entrance channel parameters.

\textsuperscript{1}Abhishek Yadav et al., Phys. Rev. C 78, 044606 (2008)
1.3 Motivation *a few questions in mind*

- Forward recoil range distributions (FRRDs): as a direct proof of fractional linear momentum transfer. Here, a significant fusion incompleteness, associated with fractional degree of linear momentum transfer (LMT) has been observed in $^{12}$C+$^{159}$Tb system. The ICF probability has been found to depend strongly on the beam energy.

- Spin-distribution measurements of residues: to probe the entry state populations in CF and ICF reactions in $^{16}$O+$^{169}$Tm system.

- Forward-to-backward yield ratios $[R_{Y(F/B)}]$ measurements: to study the pre-equilibrium emission in $^{16}$O+$^{169}$Tm system at $\approx 5.6$ MeV/A.

The EFs for several radio-nuclides produced in $^{12,13}$C+$^{159}$Tb systems via CF and/or ICF at the energies $\approx 4-7$ MeV/A have been measured employing the activation technique followed by off-line $\gamma$-spectroscopy. The experimentally measured EFs has been analyzed in light of statistical model code PACE4. The experimental details for the measurement of EFs, results and their interpretations are given in Chapter-2 of this thesis. Further, in order to confirm the findings of EFs, and also to have the direct proof of fusion incompleteness, the FRRDs for several residues populated in $^{12}$C+$^{159}$Tb system, have also been measured at three different above barrier energies i.e., $\approx 74$, 80 and 87 MeV and are discussed in Chapter-3 of the thesis. The measurements carried out with the Gamma Detector Array (GDA) set-up coupled with the Charged Particle Detector Array (CPDA), to investigate the multitude of driving input angular momenta associated with different CF and/or ICF processes in $^{16}$O+$^{169}$Tm at energies $\approx 5.6$ MeV/A have been presented in Chapter-4. In the Chapter-5 of the thesis, the results of forward-to-backward yield ratio $[R_{Y(F/B)}]$ measurements for different reaction products in a particle-$\gamma$-coincidence experiment, for $^{16}$O+$^{169}$Tm system at energies $\approx 5.6$ MeV/A, have been presented. The conclusions and future perspective are presented in the last Chapter of the thesis. The references are given at the end of the thesis.

---
Chapter 1. Nuclear reactions tool to probe the nucleus