Chapter 1

Introduction

One of the main motivations to study nuclear reactions is to understand the equilibrium process at different degrees of freedom. With the availability of accelerators and a wide variety of energetic heavy ion beams, it has been possible to investigate various macroscopic as well as microscopic features of collision processes involving complex nuclei. In low energy heavy ion collisions, apart from direct (quasi elastic, few-nucleon transfer etc..) reactions on the one hand and highly complex compound nuclear reactions on the other hand, there are also a host of processes (deep inelastic scattering, quasi fission etc.,) which are intermediate between the two extremes. The study of these intermediate processes, broadly categorized as damped nuclear reactions, is crucial in understanding the relaxation mechanism of various collective nuclear degrees of freedom. All these processes are characterized by significant damping of macroscopic motion through intrinsic nucleonic excitations. In the low energy domain, nuclear mean field is the most dominant factor and the relaxation of various collective nuclear degrees of freedom under the influence of mean field primarily determines the nature of reaction processes. As the relaxation times of various degrees of freedom are different, nature of the reaction would primarily depend on the interaction time between the colliding nuclei. As heavy ion collisions are associated with larger linear and angular momentum transfer as compared to collisions involving light ions (up to \( ^4 \text{He} \)), they open up possibilities for producing and studying
nuclei under extreme conditions (high spin, high excitation.) Moreover, by proper choice of projectile-target combination, one may also be able to produce nuclei which are very much away from the $\beta$-stability line, as well as the much sought-after superheavy nuclei. Thus, heavy ion reactions play a major role to probe into the less explored domains of nuclear physics.

1.1 Classification of nuclear reactions

Nuclear collisions leading to different reaction products is primarily a phenomenon involving strong and electromagnetic interactions and they obey a set of conservation laws. Many different reactions may occur during a collision between two nuclei. In general, a nuclear reaction can be represented by an equation in the following form:

$$a + A \rightarrow B + b$$

(1.1)

or, simply as $A(a,b)B$, where $A$ is the target nucleus, $a$ is the projectile, $B$ is the residual nucleus and $b$ is the ejected particle. There may be more than two particles in the exit channel after collision. The kinetic energy in the exit channel is less than that in the entrance channel. The interacting nuclei undergo a continuous evolution which can be inferred from the observation of energy, angle, charge, mass etc. of the reaction products. On the basis of experimental observations, Fig. 1.1 shows the general evolution of a quantum mechanical system during the interaction[1]. If the initial available energy (typically 1 to 5 MeV/u) above the interaction barrier is such that the relative velocity is considerably smaller than the fermi velocity of the nucleons inside the colliding nuclei ($\approx 40$ MeV/u), then a rapid equilibration of the system is favoured. As the perturbation and equilibration proceed, energy, angular momentum and mass are dissipated. In peripheral collisions, small kinetic energy losses are observed leading to quasi-elastic and partly damped events. As the interaction time increases, overlapping of the colliding nuclei increases leading to more nucleon exchange, so that large mass transfers are observed and
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the full kinetic energy available above the coulomb barrier can be dissipated. This leads to the formation of the dinuclear system. The dinuclear system leads to deep inelastic and capture symmetric fragmentation process. If the dinuclear system rotates for several turns due to the long interaction time then the memory of the ingoing configuration is lost and the system emerges in a symmetric mass fragmentation resembling that of a fusion-fission process. For sufficiently long interaction time the target and projectile are completely fused to form a mononucleus called the compound nucleus, where the system gets equilibrated in all degrees of freedom such as mass, energy, angular momentum etc.

Classically, one can describe the heavy ion collisions in terms of trajectories. Each impact parameter determines a unique trajectory. Therefore, the different reaction mechanisms can be classified by typical impact parameters. Fig. 1.2 shows the classification of heavy ion reactions by impact parameters. which is defined as the perpendicular distance between the centre of force and the incident direction (see Fig.1.2). Very large
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Impact parameters \( (b_{\text{el}}) \) correspond to distant collisions and are associated with elastic scattering or at most Coulomb excitation. Grazing collisions are characterized by smaller impact parameters \( (b_{\text{gr}}) \) and are classified as direct reactions, in which only few degrees of freedom are involved. These processes are also called quasi-elastic collisions. At even smaller impact parameters \( (b_{\text{DIC}}) \) the collisions become more violent. The collision partners keep their identity up to a net exchange of a few nucleons, but a large amount of energy and angular momentum is transferred from the relative motion to intrinsic excitations of the colliding ions. These processes are named as deep-inelastic collisions (DIC). In this processes the system remains together for part of a revolution only, retaining a dinuclear shape with little mass transfer between the components though the kinetic energy becomes completely relaxed. The fast \( (\delta\text{-electrons}) \) electrons are also emitted from the quasi-atom which is formed during DIC. These \( \delta \)-electrons can serve as atomic clock
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for the time-scale of DIC. For still smaller impact parameters \( b_F \), the projectile nucleus completely fuses with the target nucleus (fusion reaction) leading to the formation of compound nucleus (CN). The compound nucleus is highly excited and carries a large amount of angular momentum. Therefore, it does not live forever but decays by fission and/or evaporation of light particles.

The classification of heavy-ion collisions by relating a unique impact parameter to a classical trajectory of each type of reaction is valid if one neglects the action of fluctuating forces. Due to the action of the fluctuating forces each impact parameter contributes only with a certain probability to the different types of reactions as shown in Fig. 1.3. In figure 1.3, the trajectories are shown approaching the potential barrier between two colliding heavy ions. A trajectory (1) (with no fluctuating forces) shown in Fig. 1.3 just reaches the top of the static fusion barrier \( V_{stat} \) if no friction between the heavy ions is acting. If friction force plays a role (trajectory (2)) then the initial energy would not be able to overcome the barrier because it would lose energy on the way. Therefore, a trajectory (3) needs an extra energy, the so-called extra push, to reach the top of the static barrier. The energy necessary to reach the static barrier, when friction is involved, corresponds to the dynamical barrier \( B_{dyn} \). Since the fluctuating forces are acting besides conservative and frictional forces, there exists a bundle of trajectories rather than a single trajectory as indicated schematically in Fig.1.3. The bundle of trajectories hits the interaction barrier. Some of the trajectories overcome the barrier and some gets reflected. The distribution function thus bifurcates into a fusion branch and a branch for inelastic collisions. The latter is subdivided according to the energy loss. Trajectories with small energy losses falls in the category of quasi-elastic collisions and the trajectories with large energy losses comes under the category of deep-inelastic collisions.

The classification of different nuclear reactions are also characterized by the corresponding differential cross section \( (d\sigma/dl) \) with respect to the angular momentum \( l \) as shown in Fig. 1.4. The overlap of the different reaction types with respect to contributions
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Figure 1.3: Schematic diagram of trajectories with fluctuating forces.

Figure 1.4: Spin distribution of a heavy-ion reaction. The regions for fusion is indicted by \( \sigma_f \), region of quasi-elastic collisions by \( \sigma_{qe} \) and deep inelastic collisions by \( \sigma_{DIC} \).
of the impact parameter is indicated. The areas below the different curves correspond to the total cross section for fusion ($\sigma_F$), deep-inelastic ($\sigma_{DIC}$) and quais-elastic ($\sigma_{qe}$) collisions. The lower part of the angular momentum which is leading to fusion ($\sigma_F$) can be further divided into two parts according to the decay. The lower part of the angular momentum distribution of fusion dominantly results in evaporation residue, while the larger values contribute mainly to fission.

1.1.1 Formation and decay of the compound nucleus (CN)

It typically takes around $10^{-21}$ to $10^{-22}$s for a beam nucleus to pass a target nucleus. When these two interacting nuclei strongly interact with each other, they form a combined system called the compound nucleus (CN). In such type of reaction, the available energy is shared among all nucleons from the two collision partners which are assumed to be in statistical equilibrium with each other. The thermodynamical equilibrium occurs within about $10^{-21}$ seconds, during which the CN loses its memory of how it was formed in terms of the make up of the target and projectile nuclei. However, quantities such as total energy and angular momentum are conserved. By conservation of energy, the compound nucleus is formed at an excitation energy which depends on the centre of mass kinetic energy of the collision and the Q-value for compound nucleus formation. The compound nucleus is highly excited and has a temperature. It also carries angular momentum equal to the sum of the angular momentum of the relative motion in the entrance channel and the spins of initial collision partners. The decay follows with a certain probability to two different routes as shown schematically in Fig. 1.5. On the first route, the CN fissions, i.e. it predominantly separates into two heavy fragments of approximately equal size. One speaks about a fusion-fission process. During fission the intermediate system (CN) evaporates light particles (n, p, α) and $\gamma-$ quanta until scission when the neck is shrinking to zero. These particles are called prescission particles. After scission, the heavy fragments are still highly excited and continue to evaporate light particles and $\gamma-$quanta. These
particles are called postscission particles. It is possible to distinguish experimentally between pre and post scission particles. On the second route, the excitation of the CN is not removed by fission but solely by the evaporation of light particles \((n, p, \alpha)\) and/or by high energy \(\gamma\)-ray emission (such as giant resonance decays)\([2,3]\). Due to the effect of protons and alpha particles having to tunnel through the Coulomb barrier, charged particle emission is inhibited compared to neutron evaporation for compound systems closer to stability. Once the CN moves further to the neutron deficient side, the neutron separation energy increases and the proton separation energy decreases allowing charged particle (proton and alpha) emission to compete and often dominate over neutron evaporation. Due to the very high density of states in the highly excited compound system, the evaporated particles have a statistical energy distribution. Such particle reduce the excitation energy of the compound system by around 5-8 MeV, yet remove only \(1 \rightarrow 2\hbar\) of angular momentum. Particle evaporation continues until the system reaches a state where the excitation energy is less than the particle separation energy above the yrast line (see Fig.1.6).
The yrast state is the state of lowest energy for a given value of angular momentum. Once the system reaches the yrast state it leads to the formation of bound residual nuclei, the so-called evaporation residue (ER). It takes around $10^{-15}$ sec for a system to form residual nucleus. As Fig. 1.6 shows, the final nucleus created is determined by the entry point (relative to the yrast line) in the excitation energy/angular momentum plane. The probability for a compound nucleus evaporating a particle (usually n, p, α) is proportional to the density of final states and a barrier (Coulomb usually) transmission coefficient, given by\cite{4}

$$
T(l_i, E_p(i)) = \exp \left( \frac{-2\hbar\delta}{(2m_p(V - E_p))^\frac{1}{2}} \right)
$$

(1.2)

where $V$ is the height of the barrier and $\delta$ is its width. It is to be noted that the shape of the spectra is different for charged particles (p, α) compared to neutrons due to the effect of the Coulomb barrier. In neutron-deficient compound systems, the neutron separation energy is so high (up to 15-20 MeV), that it is larger than the height of the Coulomb
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barrier at a given excitation energy and hence charged particle emission is favored. ERs,
during the decay of compound nucleus, are formed in excited states carrying high angular
momenta. ERs get de-excited by the emission of the gamma rays to the ground state.
The emitted gamma rays, carry a valuable information on the spin distribution of ERs
and also help to identify the decay channel of the CN. After the $\gamma$—quanta emission,
$\beta$—decay is possible until one ends with a stable element of the nuclear chart. Which of the
decay routes dominates depends on the mass, excitation energy and angular momentum
of the system under consideration. The evaporation of particles during the fission process
(prescission particle emission) can be considered as a chain of bifurcation processes, which
is schematically shown in Fig. 1.7. Fission occurs with a certain probability without the
emission of a particle (first-chance fission). Also, during fission one or two neutrons
may be emitted (higher chance fission). In actual heavy ion induced fission, the decay
scheme becomes even more complicated, because other kinds of light particles (p, $\alpha$, d,
$\gamma$—quanta) are also emitted. During the formation of the CN there is also a probability
of some light particles being emitted, which are of increasing importance with increasing
bombarding energy. These particles are called pre-compound or pre-equilibrium particles.
If the intermediate complex formed in the collision is not a fully equilibrated compound
system, then there is a possibility of fast fission or quasi-fission to occur.

1.2 Theoretical Model

1.2.1 Formation of compound nucleus: Fusion

The total potential between two interacting nuclei is given by the sum of nuclear, Coulomb and centrifugal potentials,

\[ V = V_{\text{nuc}} + V_{\text{Coul}} + V_{\text{cent}} \]  \hspace{1cm} (1.3)

Typical potential (nuclear + Coulomb + centrifugal) energies \( V(r) \) as a function of ion-ion separation distance \( r \) for different values of angular momentum is shown in Fig. 1.8. In a classical picture, the projectile and target can interact in only two ways: the projectile either scatters elastically of the target or fuse with it into a compound nucleus. The projectile moves in the field of Coulomb-plus-nuclear scattering potential \( V(r) \). For a
given impact parameter $b$, the radial motion is governed by the effective potential

$$V_b(r) = V(r) + E \frac{b^2}{r^2}. \quad (1.4)$$

Now, if we consider a trajectory with an energy $E$ low enough such that an impact parameter exists for which the effective potential has a barrier and its height coincides with $E$, then this impact parameter is called the grazing impact parameter ($b_{gr}$). The corresponding radial distance defines the barrier radius $R_B$. If the projectile has an impact parameter $b > b_{gr}$, it will be reflected by the barrier. If $b < b_{gr}$, the projectile will overcome the barrier and fuse with the target. The barrier radius $R_B$ as well as the corresponding value of the scattering potential, $V_B = V(R_B) = V_{b=0}(R_B)$, depend weakly on the fusion impact parameter $b_{gr}$. Eqn.1.4 can be rewritten as

$$E = V_B + E \frac{b_{gr}^2}{R_B^2}. \quad (1.5)$$

so that

$$b_{gr} = R_B \sqrt{\left(1 - \frac{V_B}{E}\right)}. \quad (1.6)$$

The trajectories shown in Fig. 1.9 entering from the left through the annular area $2\pi b db$ will fuse, if their impact parameters satisfy $b < b_{gr}$.

The fusion cross section for them is equal to $2\pi b db$ where $b = 0$ to $b_{gr}$. The total fusion cross section is thus given by the relation:

$$\sigma_F = \pi b_{gr}^2. \quad (1.7)$$

substituting the value of $b_{gr}$ from Eqn.1.6 we get

$$\sigma_F(E) = \pi R_B^2 \left(1 - \frac{V_B}{E}\right). \quad (1.8)$$
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Figure 1.9: Schematic diagram of trajectories for the determination of classical cross section.

The classical picture of fusion has its quantal counterpart in the sharp-cut-off approximation for the transmission coefficient i.e.

\[ T_l = \begin{cases} 1 & \text{for } l < l_{gr} \\ 0 & \text{for } l > l_{gr}. \end{cases} \]  

(1.9)

The fusion cross section is given by

\[ \sigma_F(E) = \frac{\pi}{k^2} \sum_{l=0}^{l_{gr}} (2l + 1) = \frac{\pi}{k^2} (l_{gr} + 1)^2. \]  

(1.10)

In the classical limit \( l_{gr} \gg 1 \) this becomes

\[ \sigma_F(E) = \frac{\pi}{k^2} l_{gr}^2 = \pi b_{gr}^2. \]  

(1.11)

Another limitation for the formation of the compound nucleus comes from the angular momentum. A compound nucleus becomes unstable against prompt fission for angular momenta above the critical value \( l_{crit} = l_{crit}^f \). A fusion can occur if the impact parameter \( b \) is smaller than the critical value \( b_{crit} = l_{crit}/k \). If \( b_{gr} < b_{crit} \) the cut-off of the impact...
parameters contributing to fusion is given by \( b_{gr} \) as before, but if \( b_{gr} > b_{crit} \) the cut-off is provided by \( b_{crit} \). Therefore the fusion cross section is given by

\[
\sigma_F = \pi b_{gr}^2 \text{ for } b_{gr} < b_{crit} \\
= \pi b_{crit}^2 \text{ for } b_{gr} > b_{crit}.
\] (1.12)

The change in regime occurs at the energy \( E_{crit} \) at which \( b_{gr} = b_{crit} \). Using Eqn.1.6 and

\[
b_{crit}^2 = l_{crit}^2 / k^2 = \hbar^2 l_{crit}^2 / 2 \mu E,
\] (1.13)

Therefore at lower energies i.e \( E < E_d \) the fusion cross section is given by

\[
\sigma_F(E) = \pi R_B^2 \left( 1 - \frac{V_B}{E} \right) \text{ for } E < E_d
\] (1.14)

At higher energies, \( E_d < E < E_{crit} \) where other non-elastic processes besides fusion begin to take place in the region between the barrier and the nuclear interior, with the consequence that the radius inside of which fusion alone take place is no longer the barrier radius \( R_B \) but the smaller critical distance \( d \). In eqn.1.8 the quantities \( R_B \) and \( V_B \) must be replaced with \( d \) and \( V_d \),

\[
\sigma_F = \pi d^2 \left( 1 - \frac{V_d}{E} \right) \text{ for } E_d < E < E_{crit}
\] (1.15)

Here, \( E_d \) is the energy for which the effective potential \( V_d(d) \) at the critical distance \( d \) and the effective barrier height \( V_d(R_B) \) are equal. At still higher energies, \( E > E_{crit} \) the fusion is limited by the critical angular momentum \( l_{crit} \) for stability against prompt fission, i.e.

the fusion cross section is determined by

\[
\sigma_F(E) = \frac{\pi \hbar^2}{2 \mu E} l_{crit}^2 \text{ for } E > E_{crit}.
\] (1.16)
1.2.2 The One-Dimensional model

Classically, particles approach the barrier on trajectories which either lead to fusion or do not. In terms of transmission coefficient, $T_i$ is either equal to 1 (fusion) or 0 (no fusion). However, at lower energies two nuclei undergo fusion by quantal tunneling through the potential barrier\([5,6]\). The potential barrier can be approximated with an inverted parabola and the transmission coefficient can be written by the Hill-Wheeler form\([7]\):

$$T_i(E) = \left(1 + \exp\left[\frac{2\pi}{\hbar \omega_l} (V_B(l) - E)\right]\right)^{-1}. \quad (1.17)$$

where $V_B(l)$ is the barrier for angular momentum $l \hbar$. It is also normally assumed that the barrier position $R_B$ and the barrier curvature $\hbar \omega_B$ do not change with angular momentum.

The analytical expression for the fusion cross section is given by\([8]\)

$$\sigma_F(E) = \frac{\hbar \omega_B R_B^2}{2E} \ln \left(1 + \exp\left[\frac{2\pi}{\hbar \omega_B} (E - V_B)\right]\right). \quad (1.18)$$

where $V_B, R_B, \hbar \omega_B$ are the barrier height, position and curvature for $l = 0$, respectively.

At energies $E >> V_B$, Eqn.1.18 simplifies to classical formula for the capture of a charged particle by a nucleus (Eqn.1.8)\([9]\). At energies $E << V_B$ the cross section can be approximated to

$$\sigma_F(E) = \frac{\hbar \omega_B R_B^2}{2E} \exp\left[\frac{2\pi}{\hbar \omega_B} (E - V_B)\right]. \quad (1.19)$$

The description of nuclear fusion, as presented above, is based on the single parameter (i.e. on radial distance) and therefore often referred to as the one-dimensional model. During the reaction the projectile and target nuclei are considered to be inert spheres. However, trajectories which reach inside the barrier are assumed to irreversibly lead to fusion because of the onset of strong dissipation as a result of the inter-nucleon forces induced by the geometric overlap.
1.3 Decay of an equilibrated nucleus: Statistical model

The decay of the equilibrated nucleus is described in terms of statistical model. The basic assumption of the statistical model is that all decay channels that are open are on the average, equally likely to be populated. The open channel means a particular final state, specified by all quantum numbers including the magnetic quantum number, which can be reached from the initial state without the hindrance of barrier penetration. The presence of centrifugal, Coulomb or other types of potential barriers reduces the population of that particular channel by the barrier penetration probability. The statistical model says that the probability of decay to a particular channel (or group of channels $n$) is $1/N$ (or $n/N$), where $N$ is the total number of open channels. In any given measurement at a specific bombarding energy $E$ and $E + \Delta E$, individual channels will not exhibit the same cross section or probability of population, rather the cross sections will be distributed about a mean value. The modes of decay are classified by the type of radiation emitted or the final products: (i) $\gamma$-ray decay (ii) emission of nucleons ($p, n$) and clusters of nucleons ($d, t, \alpha$ etc) and (iii) fission.

1.3.1 Gamma-ray decay

The average rate at which an ensemble of nuclei with initial excitation energies in the range $E_i$ to $E_i + dE$, angular momentum $J_i$ and level density $\rho(E_i, J_i)$ emits gamma radiation of energy $E$ and multipolarity $\lambda$ to produce nuclei with final state energies $E_f$ to $E_f + dE$ and angular momentum $j$ is written as\[10\]

$$R(E_i, J_i; E_f, j) \, dE = C(\epsilon) \, \xi^{2\lambda+1} \left[ \frac{\rho(E_f, j)}{\rho(E_i, J_i)} \right] \, dE. \quad (1.20)$$

The first term in the above expression represents an average squared intrinsic matrix element that may have some dependence on $\epsilon = E_i - E_f$. Second term arises from the long-wavelength limit $\lambda_n/R_{nuc} \gg 1$, which causes the rate of emission to increase
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rapidly with the gamma-ray energy, $\epsilon_\gamma$. The third term is the phase-space of the initial and final densities of levels which is associated with reciprocity. The importance of gamma decay can be realized by the fact that they play a crucial role in the removal of angular momentum of the CN during its decay.

1.3.2 Emission of nucleons/clusters

Consider an ensemble of nuclei in equilibrium with energies $E_i$ to $E_i + dE$ and angular momenta $J_i$ that emits particles $\mu$ with kinetic energy $\epsilon$, spin $s$, orbital angular momenta $l$, and leaving the residual nuclei with excitation energies $E_f$ to $E_f + dE$ and spin $j$. The average rate of emission, summed over orbital angular momentum is given by

$$R_\mu(E_i, J_i; E_f, j, s) \, dE = \frac{1}{h} \sum_{S=|j-s|}^{j+s} \sum_{l=|J_i-S|}^{j+S} T_l(\epsilon) \frac{\rho(E_f, j)}{\rho(E_i, J_i)} \, dE.$$  

where $S = j + s$ is the channel spin. The energies $E_i$ and $E_f$ are related by $E_i = E_f + S_\mu + \epsilon$, where $S_\mu$ is the separation energy for particle type $\mu$. $T_l(\epsilon)$ is the optical model transmission coefficient for formation of a compound nucleus in a time reversed reaction of the emitted particle and the residual nucleus with excitation energy $E_f$ and angular momentum $j$. The transmission coefficient is related to the inverse cross-section ($\sigma_\mu$) and is thus given my

$$\sigma_\mu(E_i, J_i) = \frac{\pi}{k_f^2} \frac{2J_i + 1}{(2s + 1)(2j + 1)} \sum_{S=|j-S|}^{j+S} \sum_{l=|J_i-S|}^{j+S} T_l(\epsilon).$$  

1.3.3 Fission

In contrast to the decay modes discussed above, the decay rate for fission does not depend on the densities of levels or other statistical properties of residual nuclei, which are the fission fragments at infinite separation, nor depends on the properties of the compound nucleus at the point where the nucleus becomes committed to fission. This point is a transition state and known as the saddle point. The fissioning system passes through
this transition state and loses most of the energy into the deformation. Therefore, the energy available for intrinsic levels may be very small (See Fig.1.10). The transmission coefficients are taken to be unity if the total available energy is in excess of the fission barrier and zero otherwise. Thus the fission rate is given by[10]

\[ R_f(E_i, J_i; E_f, j) = \frac{2J_i + 1}{\hbar} \frac{\rho(E_f, j)}{\rho(E_i, J_i)} \]  

(1.23)

and

\[ E_f = E_i - E_B(J_i) - \epsilon' \]  

(1.24)

\( \epsilon' \) is the kinetic energy at the transition state or saddle point. \( E_B(J_i) \) is the fission barrier or saddle point energy and it depends explicitly on the angular momentum. The factor \( 2J_i + 1 \) arises from a summation over the transmission coefficients. One should also note that there will be enhancement of level density due to low lying collective excitations and this is particularly important for the level density at the saddle point of large deformation.
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1.3.4 Total decay rate

The total decay rate is the sum of all modes of decay

\[ R = R_\gamma + R_{n,p,a} + R_f \]  

(1.25)

\[ R_\gamma \, de = \sum_\lambda \sum_J \int_{E_i}^{E_f} R_\lambda(E_i, J; J; \epsilon, J) \, de \]

\[ R_{n,p,a} \, de = \sum_\mu \sum_J \int_{E_i}^{E_f} R_\mu(E_i, J; E_i - S_\mu - \epsilon, J, S) \, de \]

\[ R_f \, de = \left( \sum_J \right) \int_{E_i}^{E_f} R_f(E_i, J; E_i - E_B(J_i) - \epsilon^s, J) \, de \]

Probability for channel X

\[ P(E_i, J_i; X) = \frac{R(E_i, J_i; X)}{R(E_i, J_i)}. \]  

(1.26)

Hence cross section for channel X is given by

\[ \sigma(X) = \sum_{J_i} \sigma(E_i, J_i) P(E_i, J_i; X). \]  

(1.27)

1.4 Nuclear fusion-fission dynamics

The nuclear fission phenomenon was discovered by Hahn and Straassmann\[11\] and it is one of the earliest and most thoroughly studied of all nuclear phenomena. The mechanism of nuclear fission explained by Bohr and Wheeler\[12\] was able to describe the observed effects for a long time. Kramers in 1940\[13\], pointed out the importance of nuclear dissipation which was not considered by Bohr-Wheeler. It was generally believed that after the formation of compound nucleus (CN), the transition time up to saddle point and the fall time from saddle to scission point were very fast to be of any consequence in influencing the fission process. All the low energy fission data could be nicely explained using the saddle-point model without incorporating the effect of nuclear friction \[14\]. However, a spate of experimental data from heavy-ion induced reaction studies, carried out in the
last two decades have resulted in the interesting observation of unexpectedly large pre-scission yields of charged particles\[15\], neutrons\[16\], giant dipole resonance (GDR) decay $\gamma$ rays\[17\] and evaporation residue (ERs) cross section\[18\] from the compound system before fission. The standard statistical model was found to underestimate the pre-scission yields of particles and $\gamma$ rays. The discrepancy is found to be very large at excitation energies greater than 50 MeV. The underestimation of pre-scission particles and ER cross sections by the statistical model led one to think that the fission width calculated on the basis of phase space arguments is overestimated in statistical model at high excitation energies. The particle decay and ER formation probabilities increase sharply with excitation energy and when the temperature is around 2 MeV, the life time for particle emission becomes comparable to the relaxation time of collective variables as in fission ($10^{-21}$s).

The presence of frictional forces affect both the transient time from the equilibrium deformation to the saddle point and also the probability of fission over the saddle point. As a result of this, the Bohr-Wheeler estimate of fission width gets reduced. At this stage particle emission and ER compete with fission decay. As a result of the additional delay time brought into the fission mode due to friction, the ER formation and particle emission probabilities are enhanced. The particle decay can precede fission both during the transition stage from equilibrium to saddle point and also later from saddle to scission point\[19\], whereas ER formation can precede fission only in the transition stage from equilibrium to saddle point. The information about dissipative forces (friction) can be gathered from a study of pre-fission particles, ER cross section and gamma rays. Prefission particles, ER cross section and GDR gammas can be used as a clock to study the fusion-fission dynamics\[19,20\]. The enhanced emission of the pre-scission particles influences the fission anisotropies dramatically\[21\--25\]. The emission of these pre-fission particles carrying away energy of the order of 10 MeV per particle from the compound nucleus excitation energy, has the net effect of cooling the residual compound nucleus formed at the saddle point. According to the saddle-point model, $K_2^0$ is given as $I_{eff} T/\hbar^2$ where $I_{eff}$ is the
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effective moment of inertia and $T$ is the temperature at the saddle point. Due to presaddle emission of particles, the temperature is lowered and this in turn decreases the variance of the $K$-distribution ($K_2^2$). $K$ is the projection of $J$ along the symmetry axis. As the reduction in $l$ of the compound nucleus due to the emission of these particles is more than offset by the reduction in $K_2^2$, there is always a substantial increase of the fission anisotropy $A$. The fission anisotropy $A$ is defined as $A = 1 + \frac{\langle l^2 \rangle}{4K_2^2}$ where $\langle l^2 \rangle$ is the second moment of the compound nucleus spin distribution. This feature has to be taken into account in making calculations using the saddle-point model and can very well account for the enhanced values of anisotropies observed in several instances[24–26].

Another interesting observation made in the study of fusion fission dynamics is that the observed fission events may consist of compound nucleus (CN) and non-compound nucleus (NCN) events. The anisotropies for these latter fission-like events are generally very large and hence even a small admixture of these NCN events to the CN events, will lead to fairly large values of anisotropies. The fast fission[27–29], the quasi-fission [30,31] and the preequilibrium (PEQ) fission[32] are the three NCN processes. The abnormal behavior of the anisotropies was understood by the mechanism of PEQ[32]. The PEQ process corresponds to the case where the system passes over the unconditional saddle point (i.e. mass asymmetry relaxation has taken place) but the barrier height is not adequate to contain the system long enough to equilibrate fully in K-degree of freedom before reseparation.

The relevant collective mode was identified by Ramamurthy et al.[32] as the one having a slow relaxation time in relation to fission lifetime, viz., the tilting degree of freedom characterized by the K-quantum number. It is expected that the K-relaxation time is slower than that of energy, mass and charge equilibration and is of the order of $8 \times 10^{-21}$ s[32,33]. The fission process as we know it today is depicted in Fig. 1.11. The ground state (A), the saddle-point (B) and the scission point (C) are marked in the figure. The time upto the saddle is denoted as $\tau_{tra}$ and the time from the saddle to the scission is indicated as $\tau_{ssc}$ in Fig. 1.11. Recently, the study of fission dynamics of hot nuclei formed
in heavy-ion collisions has gained momentum because of the interest and prospects of obtaining experimentally the magnitude of nuclear dissipation coefficient[16,34].

1.4.1 Fission time scale and Dissipation

Studies of heavy ion induced fusion-fission reactions have become the main method for obtaining direct information on the large scale collective nuclear motion. One of the fundamental nuclear matter property is the viscosity. A basic example of the measurement of the transport properties of viscous nuclear matter is the mass flow in the fission process. In this process, a coherent mass motion is established inside the barrier and proceeds to fission either by tunneling through the barrier or at higher excitation energies through suitable transition states above the barrier. The time scale of this process is determined by the build-up of fission flux inside the barrier, flow across the barrier and the motion from the saddle to scission point. Any dissipation inside or outside the saddle lengthens these times. Thus one can know about the nuclear viscosity by measuring the time scale of the
1.4. NUCLEAR FUSION-FISSION DYNAMICS

fission process. Earlier studies of the fission process in the 1960s and 1970s used the kinetic energies of fission fragments as indicators of how much energy was lost from the collective process[14, 35]. Compelling evidence has been obtained that fission decay of hot compound nucleus (CN) is somewhat delayed in comparison to the statistical model prediction. This phenomenon is known as fission hindrance. The time scale of fission for highly excited heavy nuclei can be studied by measuring the yield of any combination of probes like neutrons, charged particles (proton, alpha), giant dipole $\gamma$-rays, evaporation residue (ERs) and fission fragments (FFs). The first four probes give the valuable information for all the three regimes but ERs and FFs give the information of solely pre saddle and post scission regime respectively. Experimental observations clearly reveal that there is excess yield of neutrons, charged particles, evaporation residues and $\gamma$-quanta, in comparison with the standard statistical model predictions. This excess emission from the highly excited composite system is attributed to time delay or dynamical hindrance in the fission process. It, therefore, appears that the dissipative dynamical model would provide an appropriate description of nuclear fission at higher excitation energies. This excess yield also provides the evidence of important effects in fission dynamics like (i) retardation of formation of fission degree of freedom, (ii) dissipation effects during collective motion towards the barrier and scission point, (iii) light particle and $\gamma$-quanta emission at the descent stage between the saddle to scission point.

Nuclear collision resembles collision in a medium which is highly viscous in nature at higher excitation energies and has to be treated by dynamical method. The dynamics of fission at moderate excitation energies is governed by nuclear dissipation. The dissipation occurs through the interaction of nucleons with the mean field and with each other in the vicinity of the nuclear surface, as well as through the transfer of nucleons between the two portions of evolving dumbbell like system. Therefore dissipation slows down the fission process and it has also influence on particle and gamma emission (see Fig. 1.12).

The compound nucleus is formed at equilibrium deformation. Starting from $t = 0$,
the fission motion builds up inside the barrier with time constant $\tau_D$. Thus the fission width at the saddle is given by\cite{36,37}

$$\Gamma_f(t) = \Gamma_f^0 \left[ 1 - \exp \left( -\frac{t}{\tau_D} \right) \right].$$

(1.28)

where $\tau_D$ is the delay time for the fission probability flow to reach the saddle point. This fission delay leads to the survival of CN, which in turn leads to enhanced emission of $n, p, \alpha$ particles, $\gamma$-rays, and formation of ERs. As the fission motion reaches the saddle point, the viscous diffusion process results in a reduction of the normal fission width.

Using Bohr Wheeler expression\cite{12} for normal non-dissipative, fission width, Kramers\cite{13} proposed a modified fission width

$$\Gamma_f^{\text{kramers}} = \Gamma_f^{\text{BW}} (\sqrt{1 + \gamma^2} - \gamma).$$

(1.29)

where $\gamma$ is the nuclear friction coefficient, $\gamma = \frac{\beta}{2\omega_0}$; $\gamma = 1$, $\gamma > 1$ and $\gamma < 1$ correspond to critical, overdamped and underdamped oscillations, $\beta$ is the reduced dissipation
coefficient and $\omega_o$ describes the curvature of the potential energy surface at the saddle point (barrier frequency)\[36\]. Hence the modified fission decay width is

$$\Gamma_f(t) = \Gamma^{\text{dramers}}_f \left[ 1 - \exp \left( -\frac{t}{\tau_D} \right) \right]. \quad (1.30)$$

The delay time $\tau_D$ can be expressed in terms of dissipation parameter $\beta$ or $\gamma$. For over damped situation the relation is given by\[38\]

$$\tau_D = \frac{\beta}{2\omega_i^2} \ln \left( \frac{10E_{\text{bar}}}{T} \right) = \frac{\gamma_i}{\omega_i} \ln \left( \frac{10E_{\text{bar}}}{T} \right). \quad (1.31)$$

where $E_{\text{bar}}$ is the fission barrier, $\omega_i$ is the assault frequency and $\gamma_i$ is the friction coefficient inside the saddle. Nuclear dissipation further slows down the fission motion from the saddle to scission point. The motion along this path is described by a time $\tau_{\text{ssc}}$ which can be expressed in terms of friction coefficient outside the barrier $\gamma_o$

$$\tau_{\text{ssc}} = \tau^0_{\text{ssc}} (\sqrt{1 + \frac{\gamma^2_o}{\gamma^2_i}} + \gamma_o). \quad (1.32)$$

$\tau^0_{\text{ssc}}$ being the time without dissipation. $\tau^0_{\text{ssc}}$ can be expressed as\[17,39\]

$$\tau^0_{\text{ssc}} = \frac{2}{\omega_o} R \sqrt{\frac{\Delta V}{T}}. \quad (1.33)$$

where $\Delta V$ is the potential energy difference between the saddle point and scission point, $T$ is the nuclear temperature and $\omega_o$ is the barrier frequency. Therefore when dissipation is introduced into the fission process it is described by just two parameters, $\gamma_i$ and $\gamma_o$. Fig.1.13 shows the effect of $\gamma_i$ on the fission width.

Apart from these two time delays, there is also another time, the so called formation time ($\tau_{\text{for}}$). Difference in formation times is predicted if the same compound nucleus is formed in reactions of different projectile-target mass asymmetries ($\alpha$), that are on the either side of the Businaro-Gallone critical asymmetry value $\alpha_{BG}[40]$. Taking into account all these times, the total fusion fission time scale can be written as

$$\tau_{\text{tot}} = \tau_{\text{for}} + \tau_D + \tau_{\text{ssc}}. \quad (1.34)$$
One of the important parameters in such kind of studies is the fission hindrance threshold ($E_{\text{thr}}$) which is the CN excitation energy from where the onset of dissipation takes place resulting in deviation from the standard statistical model prediction. Thoennessen et al. [41] has examined the empirical domain of validity of the statistical theory, as applied to fission data on prefission neutrons, charged particles and $\gamma$-ray multiplicities and extracted the threshold values for different probes with mass number as shown in Fig. 1.14. However, due to lack of evaporation residue experimental data in the literature, the energy threshold for this probe is not very well known.

Very few measurements on evaporation residues (ERs) [42] have been carried out to understand the fission hindrance. It is interesting to note that as a fused system moves from equilibrium position to saddle point and then saddle point to scission point, it keeps on emitting neutrons, charged particles and gamma rays. Therefore neutron, charged particle and gamma ray multiplicities are not very sensitive to whether the emission occurs before or after the traversal of saddle point. On the other hand, ER measurement is a more
Figure 1.14: The schematic diagram of extracted threshold energy $E_{\text{thres}}$, where dissipation effects start to influence the fission process in hot nuclei as a function of mass for different probes. Open circle corresponds to neutron multiplicity, solid circle corresponds to charged particle multiplicity, cross mark corresponds to GDR $\gamma$-ray multiplicity and open triangle corresponds to peripheral reactions.

sensitive method to understand fission hindrance from equilibrium deformation point to saddle point because the evaporation probability from the hot compound nuclei formed in heavy ion fusion is sensitive to the dissipation strength inside the fission barrier. If there is any reduction in the fission width due to dissipation then there is a strong probability for survival of the compound nucleus. This is manifested in evaporation residue cross section which is larger than predicted by the standard statistical model. The compound nucleus undergoing fission or surviving as an ER is decided mainly within the saddle point. Hence the measurement of ER formation probability provides the desired separation between pre-saddle and post-saddle dissipation. It is also pointed out by Frobrich et. al.[43] that the ERs are more sensitive probes rather than neutrons, charged particles, or $\gamma$-rays for studying the dynamics of fusion-fission process. The fusion-fission process is controlled both by excitation energy and the angular momentum of the compound nucleus. ERs get deexcited by emission of gamma rays. These are non-statistical gamma rays and take away two units of angular momentum[44], if the residual nuclei are good rotors (i.e. decay
process is mostly through E2 transition). These gamma rays carry valuable information on the spin distribution of ERs. The CN has a larger deformation and hence large moment of inertia at the saddle point than at the equilibrium deformation. Thus the fission barrier, which is the difference in energy of these two rotating shapes, decreases with increasing angular momentum. Fission therefore imposes the upper limit to the angular momentum carried by the ERs from heavy compound nucleus. If there is any fission hindrance then the spin population of the ERs will be enhanced with the occurrence of higher spin values\cite{45,46}. Thus the evaporation residue spin distribution is also a sensitive probe for studying fusion fission dynamics\cite{47}.

1.5 Motivation of the present work

The motivation of the present thesis was to study fission hindrance in presaddle region using two different probes. To understand the dynamical aspects several investigators carried out measurements on neutrons, charged particles\cite{19,48} and GDR γ-rays\cite{17}. Their measurements showed considerable enhanced yield compared to statistical model predictions. Different dissipation parameters have been quoted for the same system at the same excitation energy range when it has been studied using two different probes. The reason for this contradiction is not clear which is one of the reasons for carrying out the present work. As mentioned in Sec. 1.4.1 Thoennessen et. al\cite{41} quoted energy threshold for the onset of dissipation (See Fig.1.14). This energy threshold is not unique for all the probes, but rather different for different probes, especially in 200 mass region (See Fig.1.14). These discrepancies demand combined and accurate measurements involving different probes. This is another reason for performing the present experiments with a hope of contributing to this field. From the survey of literature (Chapter 2) and also from Fig.1.14, one can see that very few measurements on evaporation residue cross section have been carried out to study fission hindrance and therefore the energy threshold for this
1.5. MOTIVATION OF THE PRESENT WORK

Probe is not known. Measurement of ER formation probability is the probe which gives the desired separation between pre-saddle and post-saddle dissipation. Spin distribution is also a sensitive probe to study fission hindrance. Suppression in the fission process enhances the spin population of the ERs with the occurrence of higher spin values [46, 47]. Therefore the combined study of evaporation residue cross section and spin distribution gives a better understanding of fusion-fission dynamics than what is obtained by studying only the total evaporation residue cross section. With these motivations, the combined measurements of evaporation residue cross section and ER spin distribution have been carried out for the following systems:

1. $^{160} + ^{184}$W system in the laboratory energy range of 84 to 120 MeV.

2. $^{19}$F + $^{181}$Ta system in the laboratory energy range of 82 to 125 MeV.

Another motivation for carrying out similar measurements for two different systems by matching their excitation energies, was to understand the effect of entrance channel on fission hindrance via evaporation residue cross section and spin distribution measurements, as the two systems lie on either side of the Businaro Gallone mass asymmetry [40] point.

Experimentally there are different methods with which one can obtain the spin distribution of the compound nucleus [49]: (a) Gamma-ray multiplicity method: Conversion of multiplicity into angular momentum. (b) Isomer ratio method: The relative population of ground and the isomeric states of different spin reflects the initial angular momentum distribution. (c) Procedure based on Rotational state populations: Using rotational state populations is similar in principle to using isomer ratios and strongly relies on the statistical model for the extraction of spin distribution. (d) Analysis of Fission fragment angular distributions: The fission anisotropy is dependent on the second moment of spin distribution. (e) Analysis of alpha angular distributions: The evaporation of alpha particles is sensitive to the second moment of the compound nucleus spin distributions. (f) Method based on evaporation residue $xN$ distribu-
Moments of spin distribution directly from fusion excitation function under some assumptions: In order to make the calculations of fission fragment anisotropies using the saddle-point model, the required \( \langle l^2 \rangle \) value of the fused compound nucleus is usually obtained by fitting the fusion (or fission) excitation function.

In heavy ion fusion reactions, the residue are forward focused around zero degree and swarmed by the beam-like particles which are of the order of \( 10^{10} \) to \( 10^{12} \). There are different techniques by which one can separate out the residues from the beam like particles: (a) **Electrostatic Deflector**: In this the field which is produced perpendicular to the ion velocity deflects the ions by an amount proportional to its electric rigidity. Here, the identification of ERs is usually achieved by measuring their energy (E), time of flight and energy loss. Deflectors of this type have been used at the Legnaro National Laboratory (LNL)[50], the Argonne National Laboratory (ANL)[51]. (b) **Velocity Filter** In this the most effective rejection of beam like ions is achieved by using a combination of electric (E) and magnetic (B) fields. The ions of velocity \( v = E/B \) are undeflected as they pass through the filter. Such kind of facilities is available at Brookhaven National Laboratory (BNL)[52], Australian National University[53]. (c) **Recoil Mass Spectrometer**: These separators have high beam rejection capability, which is attained by using suitable combination of electric (E), magnetic fields (B) and focusing elements. The ERs are separated from the beam background according to their \( E/q \) and \( p/q \) values by electric and magnetic fields, respectively. The spectrometers in this category are Rochester Recoil Mass Spectrometer[54], CAMEL[55], JAERI-RMS[56], EMMA[57], Fragment Mass Analyzer[58], Heavy Ion Reaction Analyzer[59]. (d) **\( \gamma \)-ray yield measurements** In this method, the characteristic \( \gamma \)-rays of evaporation residues are measured. This method can be adopted both in online and offline measurements. In online, the characteristic \( \gamma \)-rays are detected with high purity Germanium (HPGe) detectors. In offline the residues are
stopped in a catcher foil and γ-rays associated with longer half lives are detected[60]. (e) **X-ray yield measurements** In this method[61,62], the ERs are trapped in a catcher foil and the delayed X-rays are observed offline. The thickness of the catcher foil is adjusted for stopping the evaporation residues and allowing the contaminant products to be transmitted. The X-ray yield is measured offline using a X-ray detector. Absolute cross section is deduced by normalizing the X-ray yield to the Rutherford scattering yield.

### 1.6 Plan of the thesis

Following the general introduction on heavy ion induced fusion-fission reactions and the motivation of the thesis in chapter 1, chapter 2 gives a brief review of the existing literature on fusion-fission dynamics and the international status of the present work. Chapter 3 describes the details of the experimental setup used for the evaporation residue cross section and spin distribution measurements. Chapter 4 represents the data analysis procedure and experimental results of both the systems. Chapter 5 discusses the model analysis and the interpretation of the results. Chapter 6 deals with the experimental evidence of the entrance channel effect on fission hindrance. In chapter 7 the results are summarized, conclusions from the present work are derived and the scope of future work is highlighted.
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