

# Chapter 1

## Introduction

For the last several decades heavy ion reactions have been very useful to derive the information about nuclear properties on structure and reaction dynamics. The study on nuclear reactions has been an integral part ever since the development of particle accelerator facility. Nuclear reaction can only take place when two nuclei or a nucleon and a nucleus or nucleon and nucleon come together at very close contact where they feel strong nuclear forces [1]. Thus, the particle accelerator facility has also opened up the door to understand the behavior of nucleus at high temperature and angular momentum. In terms of classical description, in order to test the details of particular nuclei it is necessary to bombard the object nuclei (target) with the incident (projectile) nuclei having wavelength  $\lambda$  which is shorter than the size of the object nuclei. However, the quantal or wave effects are important and quantum mechanics is required for a quantitative description of the phenomena in the energy domain (0-1000MeV) in nuclear physics. When projectile is scattered off a target nucleus, the outcome mainly depends on a combination of three factors:

- (i) The reaction mechanism
- (ii) Nature of interaction between the projectile and the target
- (iii) The internal structure of the nuclei involved.

Nuclear reaction is a wide subject by itself that focuses on various aspects of nuclear matter. Nuclear reaction studies can be done by choosing different interacting nuclei as well as bombarding energies of the projectile nuclei [1, 2]. In case of lighter projectiles such as  $p$  and  $\alpha$  the type of reactions are limited to the compound nucleus (CN) and direct reactions. However, in heavy ion reaction large amount of excitation energy and angular momentum can be imparted to the CN. This can lead to the synthesis of super heavy elements.

## 1.1 Types of reactions

Different reactions can take place when two atomic nuclei collide. For typical reaction such as:  $A + a \rightarrow b + B$ ,  $A + a$  is known as initial or entrance channel and  $b + B$  is known as exit channel. Depending on the nature of the final outcome, nuclear reaction can be classified in the following manner:

**(1)Elastic scattering :** In the elastic scattering, intrinsic states of interacting particles remain unchanged before and after the collision ( $Q=0$ ). Kinetic energy is also same before and after scattering in the center of mass system. This is a peripheral collision in terms of impact parameter. The measurement of this cross section is important because its analysis yields the parameters of the optical potential. Typically, this channel can be written as:  $a+A \rightarrow A+a$

**(2)Inelastic scattering:** In this type of scattering, interacting particles remain unchanged before and after scattering but any or both of the interacting particles may be excited through mutual excitation process with reduction in initial kinetic energy,  $a+A \rightarrow A^* + a'$ . The cross section for such inelastic scattering provides information on the nuclear spin and parity of the excited states.

**(3)Pick up reactions:** In this type of reaction, projectile gains the nucleons from the target nucleus as it passes from the periphery of the target nucleus. The schematic picture is shown below (Fig. 1.1):

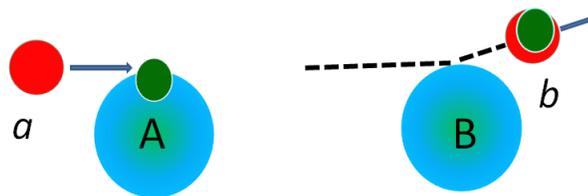


FIGURE 1.1: A schematic picture of pick up reaction.

(4)**Stripping reactions:** In this type of reaction, projectile transfers the nucleons to the target nucleus as it passes from the periphery of the target nucleus. The schematic picture is shown below (Fig. 1.2):

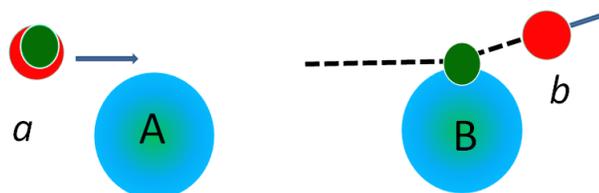


FIGURE 1.2: A schematic picture of stripping reaction.

(5)**Knock-out reactions:** In this kind of reactions, a nucleon or light nucleus get ejected from the target nucleus by the projectile. This will produce three particles in the final state. In this reaction the projectile remains free before knocking the target nucleon or light nucleus, it is also known as quasi-free scattering (Fig. 1.3).

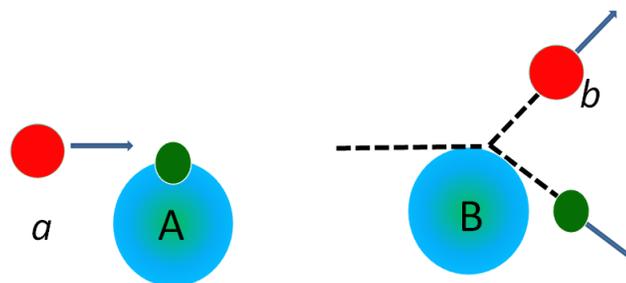


FIGURE 1.3: A schematic picture of knock-out reaction.

In the direct interaction process two nuclei make just glancing contact. For this reason these types of reactions are also known as peripheral reactions. It is assumed that in this kind of reactions nuclear particles enters or leave the target nucleus without disturbing other nucleon that are available in the nuclear shell. The time span for these kind of reactions are  $\sim 10^{-22}$  sec. Direct reactions may proceeds

from initial to final partition without going through the intermediate state. Direct reactions are very suitable in providing information regarding the relation (overlap) between the ground state of target nucleus and a ground or a particular excited state of a residual nucleus.

**(6) Compound nuclear reactions:** The collision process between two nuclei, can lead to the formation of compound nucleus with very high angular momentum and excitation energy  $E^* = E_{c.m.} + Q$ . The compound nucleus sustains until its energy gets shared uniformly among all the constituent nucleons. Typical life span of this compound nucleus is  $\sim 10^{-16}$  Sec. The resultant compound nucleus carries very high excitation energy and broad range of angular momentum, which it may lose in different ways by emitting particles like protons, neutrons,  $\alpha$  particles,  $\gamma$  rays, and for very heavy compound nuclei, it fissions out into two medium mass nuclei, as shown in Fig.1.4. To visualize these processes considering the nucleus as a liquid drop does help. The compound drop resulted from the two colliding droplets, which is at high excitation energy and at a high temperature decays or cools in terms of the evaporation of one or more of its constituent particles.

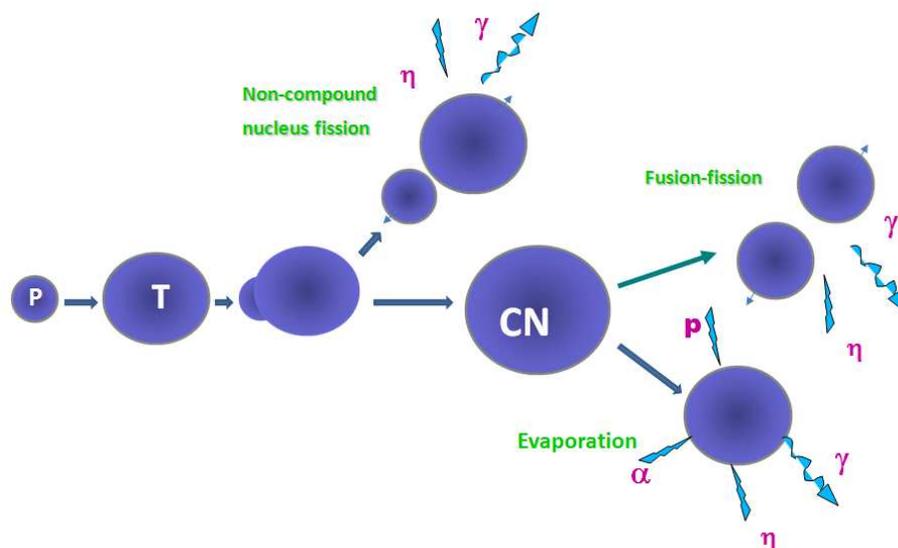


FIGURE 1.4: The formation and the decay of a compound nucleus.

Classically, until the identity of projectile and target nuclei does not diminish, these nuclei can be considered as moving in classical trajectories. Considering the impact parameter  $b$  or the corresponding angular momentum  $l$ , three different

types of reactions can be classified. For example, (i) Distant collision ( $b > b_{gr}$ ): These collisions are purely determined by Coulomb field. This can lead to the excitations that are induced by the mutual Coulomb interaction between the nuclei. (ii) Grazing collision ( $b \approx b_{gr}$ ): The grazing impact parameter can be defined as the impact parameter of the grazing trajectory that lead to considerable amount of nuclear interaction between nuclei. At this impact parameter nuclear interaction is small in nature. Direct reactions may take place at this impact parameter. (iii) Close collision ( $b < b_{gr}$ ): These type of collision occurs for smaller grazing impact parameter ( $b_{gr}$ ), where a strong disturbance of the projectile and target may take place by strong mutual nuclear interaction. This may form the compound nucleus (CN) or dissipative collision may also take place. Classical scattering phenomena are also important in dissipative collisions. The scattering which occurs at  $d\theta/db=0$  is known as rainbow scattering and the corresponding angle is a rainbow angle ( $\theta_r$ ) [3].

## 1.2 Reaction cross section

A quantity that measures the probability of a given nuclear reaction can be termed as reaction cross section. The number of particles emitted per unit time is proportional to the incident flux as well as number of target nuclei. So, the expression for deriving reaction cross section ( $\sigma_{cross}$ ) in  $4\pi$  solid angle for any reaction channel can be given as:

$$\sigma_{cross} = \frac{N_e}{N_p \times N_t} \quad (1.1)$$

Where,

$N_e$  = Number of particles emitted

$N_p$  = Number of particles incident per unit area

$N_t$  = Number of target nuclei within the beam

To obtain the total reaction cross section, for a given bombarding energy the reaction cross sections can be summed for all different channels which are discussed in the earlier sections. Different channels correspond to nuclei in different energy states as there is no quantum interference between the corresponding probability amplitudes. The sum of the reaction cross sections for all of the non-elastic (other than elastic) channels can be defined as total reaction cross sections. The total cross section can be obtained by simply adding the cross sections for elastic and non-elastic channels.

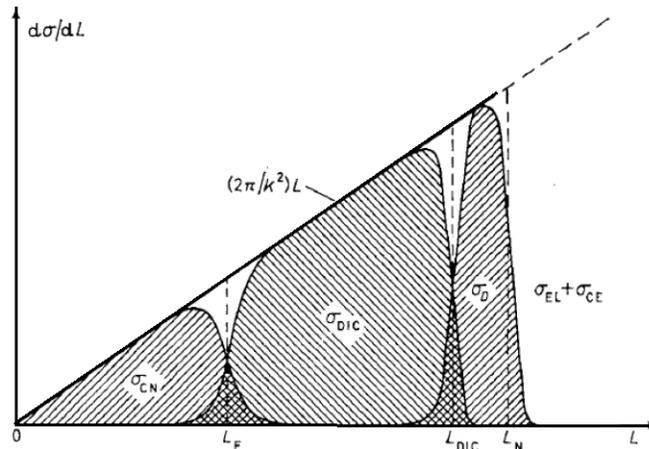


FIGURE 1.5: Total reaction cross-section into different components as a function of the orbital angular momentum ( $l$ ), taken from the Ref. [4].

Decomposition of the total reaction cross-section into different components can be understood by plotting it as a function of the orbital angular momentum [4].

From the Fig. 1.5, it can be understood that at  $l = l_f$ , compound nuclear reactions take part which includes fusion, compound evaporation, fission). At  $l_f < l < l_{DIC}$  direct reactions occurs which include quasi-elastic scattering processes and deep inelastic scattering. At  $l > l_n$  elastic scattering and Coulomb excitation play a role in contributing to the total reaction cross section.

## 1.3 Weakly bound, Exotic nuclei, Halo nuclei and Borromean systems

- **Weakly bound nuclei :** Weakly bound nuclei possess smaller binding energy as compared to the tightly bound nuclei (6-8MeV). Typical breakup threshold energy for stable weakly bound nuclei such as  ${}^6,7\text{Li}$  and  ${}^9\text{Be}$  varies in the range, from 1.5 to 2.5MeV. These kind of loosely bound nuclei show long tail in the density distribution.
- **Exotic nuclei:** Exotic nuclei are very unstable in nature and typically decay by  $\beta$  emission ( ${}^6\text{He} \rightarrow {}^6\text{Li}$  ( $t_{1/2} \simeq 807$  ms)). These nuclei lie very far from the valley of  $\beta^-$  stability. These nuclei are given various nomenclatures, such as, halo nuclei, borromean nuclei etc.
- **Halo nuclei:** With the advent of sophisticated accelerator facility, it is possible to achieve radioactive ion beams. These kind of nuclei can be described as having a core surrounded by a veil of dilute nuclear matter, extending into the classically forbidden region. This veil is referred as ‘halo’. One or two weakly bound nucleons with a large probability of presence beyond the range of the potential. Most studied halo nuclei are  ${}^{11}\text{Be}$ ,  ${}^{11}\text{Li}$ , and  ${}^6\text{He}$ .
- **Borromean systems:** These are three-body systems with no bound binary sub-systems. such as  ${}^6\text{He}$  and  ${}^{11}\text{Li}$ , none of their two-body subsystems are bound. For example,  ${}^6\text{He}$  can be described as a bound three-body  $\alpha + n + n$  system with no bound states of  $\alpha + n$  or  $n + n$ . Different kind of nuclei are shown in the section of the Segre chart, Fig. 1.6.

The nuclear reactions that involve the nuclei far from the stability valley are of paramount importance in nuclear astrophysics. These nuclei may carry different structure (level spacing, magic numbers) as compared to normal nuclei. But, the difficulties such as short lifetimes, small beam intensities that are associated with the usage of exotic beams, makes a limit to the wider study with such nuclei.

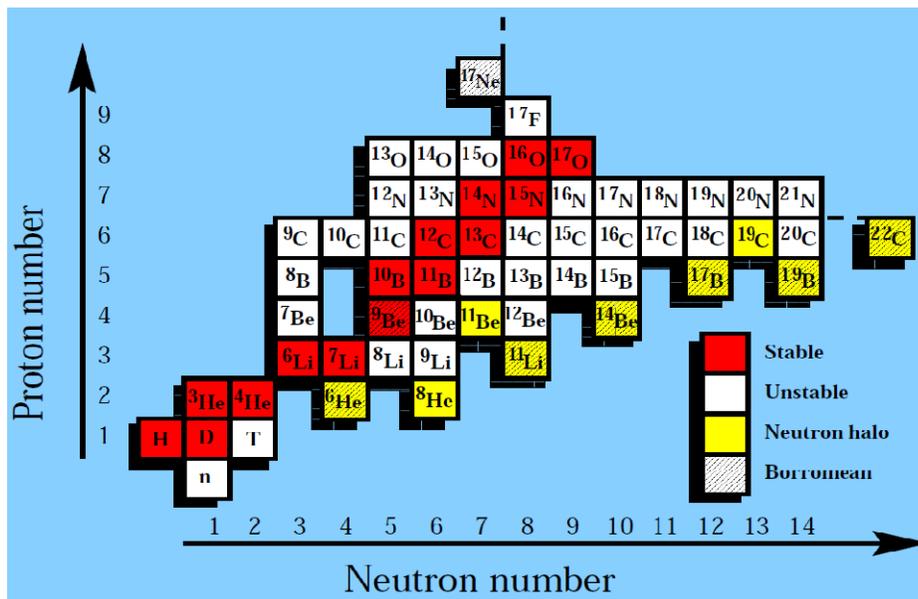


FIGURE 1.6: The section of the Segre chart, taken from the Ref.[5].

However, in this direction nuclear reaction studies have taken great interest with the availability of stable weakly bound nuclei ( ${}^6,{}^7\text{Li}$  and  ${}^9\text{Be}$ ).

## 1.4 Studies involving weakly bound nuclei

### 1.4.1 Elastic scattering

Extensive studies on elastic scattering angular distributions using weakly bound nuclei, have been carried out both experimentally as well as theoretically. Most of these were performed for widely available  ${}^6,{}^7\text{Li}$  beams. Elastic scattering angular distribution measurements is an alternative to probe the breakup coupling effects on different reaction channels. It is useful in studying energy dependences of potential parameters as a function of bombarding energies. The behavior of potential parameters that have been observed at near barrier energies shows different trends as compared to the behavior that has been seen in case of tightly bound nuclei. In the case of elastic scattering with tightly bound nuclei it has been observed that the magnitudes of the real and imaginary potential remains constant at higher energies but in the vicinity of the Coulomb barrier it shows a localized peak in

real potential with a corresponding decrease in imaginary part of the potential. This particular trend as shown in Fig. 1.7(a) is named as ‘Threshold Anomaly (TA)’ [6, 7, 8]. This behavior is understood to occur because of the coupling of elastic channel to other reaction channels that produces an attractive polarization potential below the Coulomb barrier energies. As a result the real potential increases at lower energies. Whereas, in the case of loosely bound nuclei opposite features have been observed at near barrier energy region, where the imaginary part of the potential increases with a corresponding decrease in real part of the potential. Currently, this variation of the potentials with respect to energy has been manifested as a ‘breakup threshold anomaly (BTA)’ as shown in Fig. 1.7(b) [9]. There have been many measurements on elastic scattering involving stable weakly bound [10, 11, 12] and radioactive nuclei [13, 14, 15] with some contradictory observations. From the theoretical point of view, Continuum Discretized

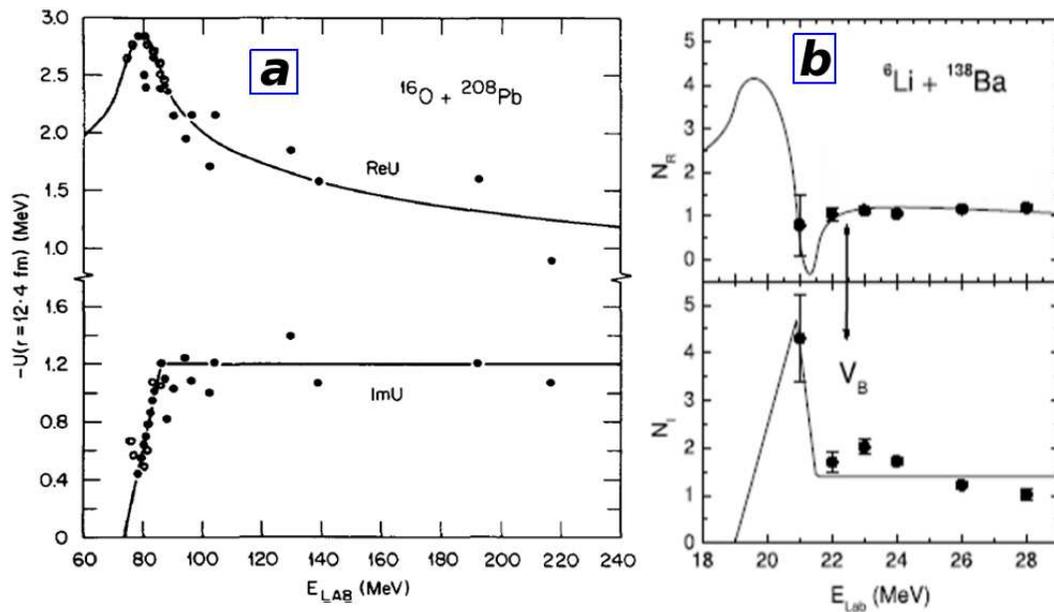


FIGURE 1.7: (a) Example of Threshold Anomaly and (b) Breakup Threshold Anomaly.

Coupled Channels Calculation (CDCC) has been a reliable formalism to understand the breakup coupling effects via elastic scattering angular distributions. The nature of the dynamic polarization (DPP) potentials have been derived from the CDCC calculations and studied as a function of energy for more qualitative understanding of the effect of breakup coupling on other reaction channels. It has

been seen that breakup coupling gives more repulsive real DPP and less attractive imaginary DPP, as the energy reduces from the barrier point. This shows opposite scenario that has been observed in the case of tightly bound nuclei. Currently, in the scattering study with  ${}^6\text{Li}$ , a clear observation has been made on ‘BTA’. However, no clear idea on the presence of the ‘TA’ could be made for  ${}^7\text{Li}$  as it is weakly bound nuclei with bound state at 477 keV. However, for  ${}^9\text{Be}$  also, there have been different results. For example for  ${}^9\text{Be} + {}^{208}\text{Pb}$  system, threshold anomaly has been seen but for the  ${}^9\text{Be} + {}^{27}\text{Al}$ ,  ${}^{64}\text{Zn}$ ,  ${}^{144}\text{Sm}$ ,  ${}^{209}\text{Bi}$ , TA, has not been observed[10, 16, 17, 18, 19, 20].

### 1.4.2 Fusion excitation function

Fusion is a process where two heavy ions collide and form a compound nucleus. The process of fusion changes with the nature of incident nuclei such as large breakup threshold (tightly bound nuclei), small breakup threshold (weakly bound stable and unstable nuclei). This phenomena also depends on the type of target nuclei as well as interaction energies that vary from below to well above the Coulomb barrier energy. Unlike the tightly bound nuclei, weakly bound nuclei have very small breakup thresholds, which affects largely the fusion process by enhancing or suppressing the fusion cross sections. Till date many experiments have been carried out for measuring fusion cross sections. Different techniques for measuring fusion are briefly discussed in the Ref. [21]. Two categories, direct and indirect methods have been adopted to measure the fusion cross sections. In the direct technique the detection of the charged evaporation residues or fission fragments produced in the decay of the Compound nuclei are involved. On the other hand, the indirect method involves detection of particles and radiation originated in the decay of the residual nuclei. While discussing fusion reaction in case of weakly bound nuclei, several concepts of fusion processes should also be considered that may contribute to the total fusion cross sections. These are listed below:

- *Direct complete fusion (DCF)*: whole projectile fuses with the target nucleus.

- *Sequential complete fusion (SCF)*: It is related with the fusion of projectile fragments. All the fragments fuse with the target nucleus.
- *Incomplete fusion (ICF)*: Partial fusion of projectile's fragments occurs.
- *Direct breakup*: Neither of the fragments fuses with the target nucleus.

Experimentally direct complete fusion (DCF) cannot be distinguished from the sequential complete fusion (SCF). Their sum that is a complete fusion (CF) only can be measured. The summation of ICF and CF gives total fusion cross sections. At above the Coulomb barrier energy, the observed elastic breakup cross sections are smaller in magnitude while at sub-barrier energies; the elastic breakup has large cross sections as compared to the complete fusion cross sections, Fig. 1.8. In order to understand the characteristic of the fusion cross sections, several theoretical efforts have also been made.

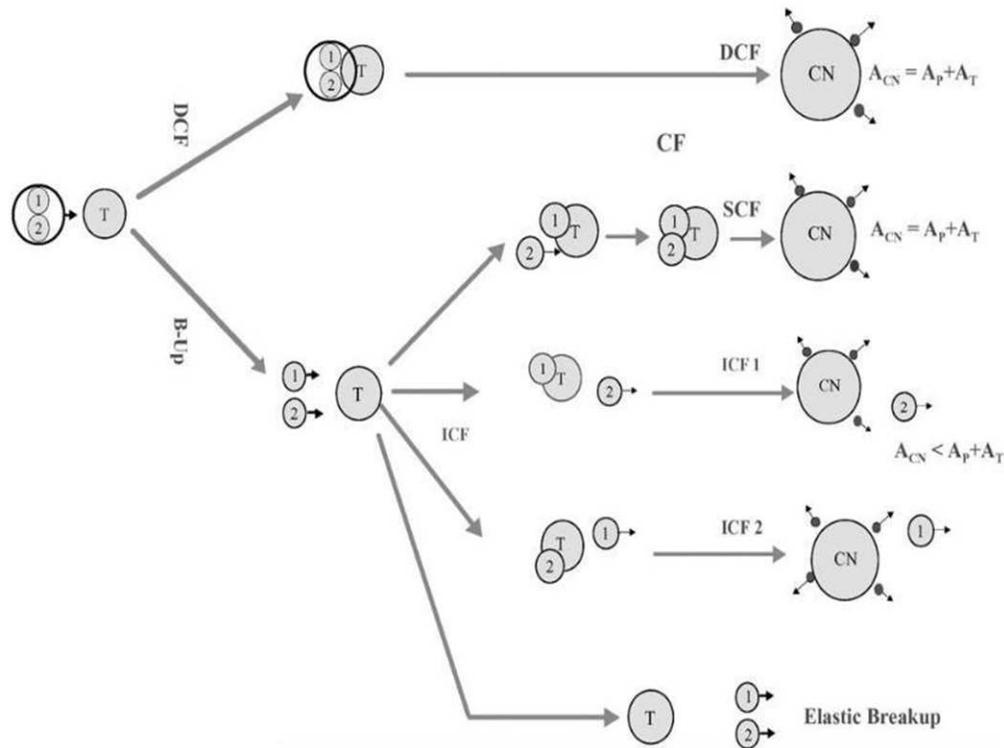


FIGURE 1.8: Schematic picture of the projectile breakup associated with the different possible fusion channels, taken from the Ref. [21].

From the CDCC calculation of reactions involving weakly bound nuclei, an enhancement and suppression in the fusion cross sections is observed at below and

above the barrier energy regime respectively. So far as the complete fusion cross sections at above the Coulomb barrier energy are concerned in comparison to the theoretical calculations without including any coupling, the experimental results have shown about 10-30 % suppression. However, the total reaction cross sections are not observed to be affected by breakup channel. To compare the reaction cross sections in different nuclear reactions, many reduction methods were used. In the Ref.[22], UFF has been used for the comparison of many reaction systems. From the Wong's formula that is,

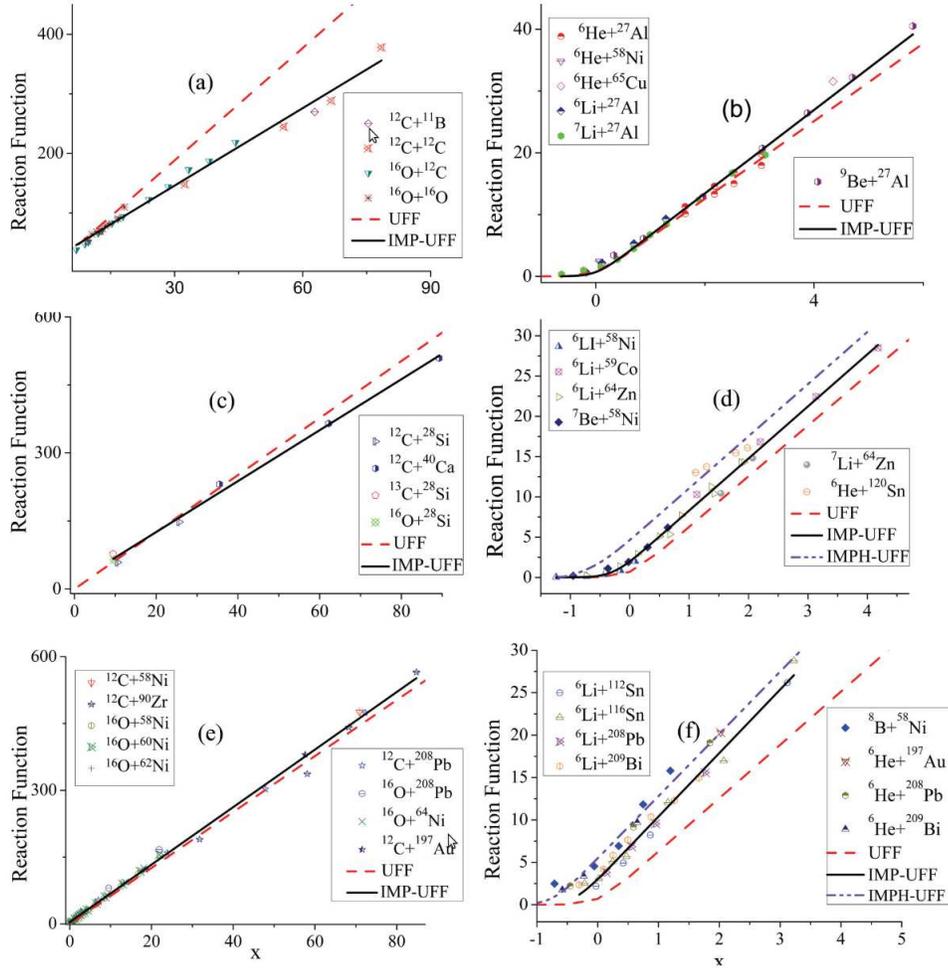


FIGURE 1.9: Reaction functions in collision of tightly and weakly bound nuclei using UFF and improved UFF(IMP-UFF). IMP-UFF indicates the fitting of halo nuclei, taken from the Ref. [23].

$$\sigma_F \simeq \sigma_F^W(x) = R_B^2 \frac{\hbar\omega}{2E} \times \ln \left[ 1 + \exp \left( \frac{2i(E - V_B)}{\hbar\omega} \right) \right] \quad (1.2)$$

Where,  $V_B$ ,  $R_B$  and  $\hbar\omega$  are the barrier energy, radius and curvature (parabolic barrier assumed), respectively, and  $\sigma_F$  is the fusion cross section, a system independent Universal Fusion Function(UFF),  $F_0(x)$  is defined by,

$$F_0(x) = \ln [1 + \exp(2\pi x)] \quad (1.3)$$

Where,  $x$  is the reduced energy. However, in a very recent work, [23], a modified phenomenological formula has been represented to compare the total reaction cross sections among different systems involving weakly bound nuclei for different barrier energy regime as shown in the Fig. 1.9. For the better reproduction of experimental data three additional dimensionless terms ( $I$ ,  $M$ , and  $P$ ) were introduced to the UFF,

$$F_{tot}(x) = IM \ln [1 + \exp[2\pi(x + p)]] \quad (1.4)$$

Here, the parameter  $I$  indicates the Coulomb barrier dependency of the modifications in the cross section,  $M$  gives enhancement of the cross section for weakly bound nuclei systems. In case of tightly bound nuclei it was taken to be 1, with assumption of no coupling or weak coupling with the breakup channel. The parameter  $P$  modifies the Coulomb barrier height to adjust the collision energy where the reaction function starts to increase sharply.

This method has lead to the conclusions such as, (i) in the reaction with the same projectile and same energy range, as the target becomes heavier, the modified radius becomes larger and therefore the value of total reaction cross section becomes large. (ii) Compared to that of tightly bound nuclei, for weakly bound projectile, the reaction cross sections are observed to be large because of the dynamic effects of these nuclei.

### 1.4.3 Fusion barrier distribution

The representation of fusion barrier distribution has been proved an effective tool in the investigation of different reaction channel coupling effects on fusion excitation function. The concept of fusion barrier distributions arise due to the effect of coupling between relative motion and many degree of freedoms such as breakup, transfer, inelastic events. Classically, when projectile incident on a target, either it can be elastically scattered or undergo fusion. This suggests that there is a direct relationship between the fusion cross section and the elastic-scattering differential cross sections, because any loss from the elastic channel may contribute to the fusion channel [24].

For angular momentum  $l\hbar = 0$ , the ratio of  $d\sigma_{el}/dR$  at  $180^\circ$  is equivalent to the reflection coefficient and therefore  $T_0 + R_0 = 1$ . The corresponding transmission coefficient is given by,

$$T_0 = \frac{1}{\pi r^2} \times \frac{d(E \cdot \sigma_{Fus})}{dE} \quad (1.5)$$

Where,  $r$  is the fusion radius,  $\sigma_{Fus}$  is the fusion cross sections at particular energy. The differentiation of the transmission coefficient ( $T_0$ ) with respect to the energy ( $E$ ) gives fusion barrier distribution for a particular system as given below.

$$D_f = \frac{dT}{dE} = \frac{1}{\pi r^2} \times \frac{d^2(E \cdot \sigma_{Fus})}{dE^2} \quad (1.6)$$

This gives basically a delta-function. However, in a quantum-mechanical description, the concept of tunneling, replaces the delta function by a Gaussian-like function.

Now, the simple and easy alternative to obtain fusion barrier distribution by reflection coefficient ( $R_0$ ), is a quasi-elastic scattering at backward angle. As discussed earlier, from the relation  $T_0 + R_0 = 1$ ,  $T_0 = 1 - R_0$ .

$$\frac{dT_0}{dE} = -\frac{d\left(\frac{\sigma_{QE}}{\sigma_R}\right)}{dE} \quad (1.7)$$

Where,  $(\frac{\sigma_{QE}}{\sigma_R})$  is the quasi-elastic channel which is normalized by Rutherford scatterings. Thus, fusion barrier distribution can also be obtained from the quasi-elastic measurement. This method has many advantages over the method of obtaining barrier distributions from the fusion excitation function. In a quasi-elastic scattering method, only single derivative of  $(\frac{\sigma_{QE}}{\sigma_R})$  is needed to obtain the fusion barrier distribution, while double derivative of  $(E.\sigma_{Fus})$  has to be taken for fusion excitation function. Also, the corresponding fusion cross sections should be of high precision as one has to deal with double derivative of  $(E.\sigma_{Fus})$ . However, limitations on accuracy arise while measuring fusion cross section such as efficiency etc.

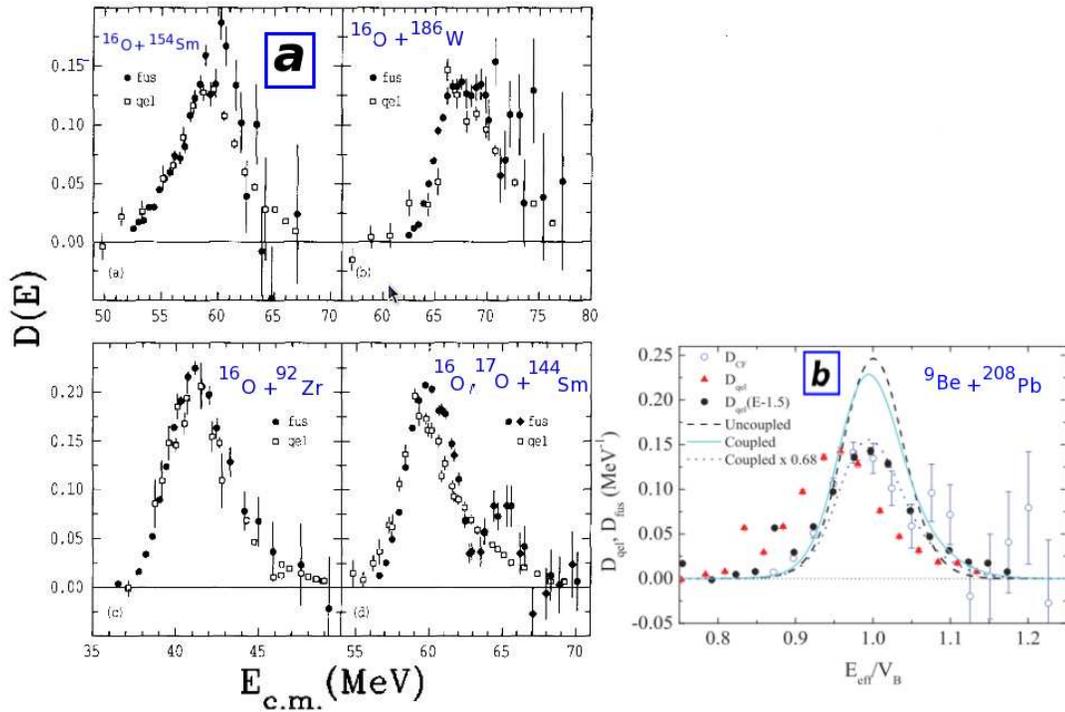


FIGURE 1.10: Fusion barrier distributions from quasi-elastic and fusion excitation functions in case of (a) tightly bound nuclei and (b) weakly bound nuclei.

A comparison for fusion barrier distributions from quasi-elastic and fusion excitation functions in the reactions involving tightly and weakly bound nuclei is shown in the Fig. 1.10 [24, 25]. Unlike the reaction with tightly bound nuclei, in the reaction involving weakly bound nuclei, the most important channels such as breakup and breakup followed by transfer, are responsible for not giving the actual fusion barrier distribution. For example, in the case of  $^{16}\text{O} + ^{92}\text{Zr}$ ,  $^{144}\text{Sm}$ ,

$^{154}\text{Sm}$  and  $^{186}\text{W}$  systems (Fig. 1.10(a)), the quasi-elastic scattering and fusion excitation function measurements give similar barrier distributions. However, in the case of weakly bound nuclei, it was observed that the barrier distributions, derived from quasi-elastic scattering reproduces actual fusion barrier distributions only when breakup part is included in the elastic + inelastic part (Fig. 1.10(b)). This suggests that in the reactions with weakly bound nuclei, the observed barrier distribution can be termed as capture barrier distribution.

#### 1.4.4 Quarter point angle

Quarter point angle is basically termed as grazing angle. At this angle, elastic cross section falls to one quarter of  $\sigma_{Ruth}$ . Quarter point angle is one of the reaction parameter that can be used to study the static and dynamical effects of interacting nuclei. The equation for calculating quarter point angle is given below:

$$\theta_{1/4} = 2arcsin \left[ \frac{1}{\left[ \frac{2E_{c.m.}}{V_{Coul}} - 1 \right]} \right]. \quad (1.8)$$

Different reaction systems can be directly compared using the experimental and theoretical values of quarter point angle. Recently, this new methodology has been adopted for light weakly bound and halo projectiles [26]. In this method the experimental and theoretical values of quarter point angle is compared for tightly bound, weakly bound and halo nuclei as shown in the Fig. 1.11, [26]. It has been seen that the coupling of different reaction channels such as direct breakup, breakup followed by transfer or pick up has similar strengths. The deviation from the theoretical value for quarter point angle was smaller for tightly bound projectiles due to small coupling effects, which is contrary to the weakly bound nuclei.

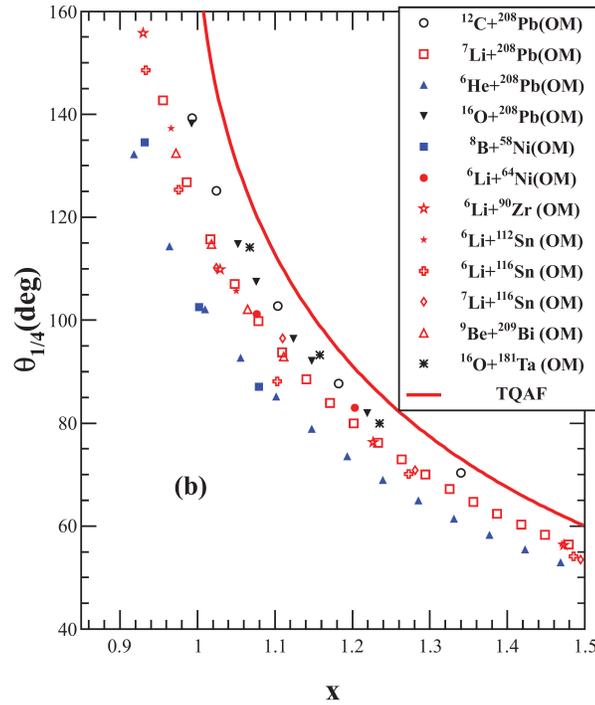


FIGURE 1.11: Comparison for Quarter point angles among different reaction systems.

## 1.5 Motivation of the study

The main motivation of the present thesis is to investigate the influence of breakup coupling on elastic scattering and fusion reaction channels by using stable weakly bound nuclei ( ${}^6,{}^7\text{Li}$ ). These nuclei have nature of loosely bound due to the lower breakup thresholds and larger rms radii in comparison to those of tightly bound nuclei. The breakup thresholds for  ${}^6,{}^7\text{Li}$ ,  ${}^9\text{Be}$  nuclei is from 1.47MeV to 2.47MeV and for neutron halo it is less than 1 MeV while the average separation energy in stable nuclei is about 6-8 MeV. The weakly bound nuclei  ${}^6,{}^7\text{Li}$ ,  ${}^9\text{Be}$  are easily available with much better intensity in comparison to radio active ion beams (RIBs). Therefore, nuclear reaction studies with  ${}^6,{}^7\text{Li}$ ,  ${}^9\text{Be}$  play a crucial role in giving glimpse of nuclear reactions involving radio active ion beams (RIBs), which has wide applications in the field of astrophysics and production of nuclei near the drip lines. Since the last few decades several experiments have been performed with stable and weakly bound projectiles. A variety of theoretical approaches have been developed in order to study the projectile coupling effects on different reaction channels, mainly, elastic and fusion. The structure of projectile/target

strongly affects the reaction dynamics at near barrier energies. In the literature many contradictory observations were made on the presence or absence of ‘Threshold Anomaly’. For example, in the reactions with weakly bound nuclei  ${}^7\text{Li}$ ,  ${}^9\text{Be}$  and heavy mass target  ${}^{208}\text{Pb}$  the so called threshold anomaly (TA) is observed, but not in the case of  ${}^7\text{Li} + {}^{138}\text{Ba}$  and  ${}^9\text{Be} + {}^{209}\text{Bi}$  [27, 28, 29]. The systems  ${}^6\text{Li} + {}^{112,116}\text{Sn}$  [30] and  ${}^6\text{Li} + {}^{209}\text{Bi}$  [31], have shown the existence of the so called ‘Breakup Threshold Anomaly (BTA)’. Also, in the case of light mass systems  ${}^{6,7}\text{Li} + {}^{28}\text{Si}$ , [32, 33] and  ${}^9\text{Be} + {}^{27}\text{Al}$ ,  ${}^{64}\text{Zn}$  [16, 18] usual ‘TA’ have not been seen. There are also measurements on elastic scattering for the  ${}^7\text{Li} + {}^{27}\text{Al}$  system reporting the absence of ‘TA’. The projectile breakup may lead to suppression in fusion cross sections due to the loss of flux in incident channel or it may enhance the fusion cross sections by coupling to elastic and other reaction channels in the below barrier energy regime. Thus there are many conflicting results that have been found in the literature in different mass region. Fusion enhancement at the sub-barrier energies and suppression at above the Coulomb barrier energies have been observed in reactions with heavy mass target. There are very few measurements exist in the literature on fusion reactions with light mass systems at sub and near barrier energies. For instance, I. Padron et al., [34] have measured total fusion cross section for the system  ${}^7\text{Li}$  on  ${}^{27}\text{Al}$  at well above barrier energies and have shown no evidence of suppression of the total fusion cross sections due to the breakup of the projectile. K. Kalita et al., [35] also have obtained fusion excitation function using the same system at above barrier energies which showed good agreement with the coupled-channels calculations using CCDEF code. In the reaction of projectile  ${}^7\text{Li}$  with neighboring target  ${}^{28}\text{Si}$  an enhancement in the complete fusion cross section has been reported at near and sub barrier energies [36]. Whereas, A. Pakou et al., [37] have reported that results are in good agreement with the one dimensional barrier penetration model (1D BPM) calculations. For  ${}^7\text{Li} + {}^{27}\text{Al}$  system, the fusion data are available at above barrier energies. However, for  ${}^7\text{Li} + {}^{27}\text{Al}$  system, some preliminary data on fusion cross-section measurement are reported in a conference paper [38], at near- and sub-barrier energies, which are much scattered in nature. Therefore, one cannot conclude about the enhancement or suppression in

the fusion cross sections at this energy regime. Neither experimentally nor theoretically, have simultaneous measurements for elastic and fusion cross sections. Thus it has created opportunity for  ${}^7\text{Li} + {}^{27}\text{Al}$  reaction to be analyzed in terms of CDCC-CRC calculations for this system. Further, the study of elastic scattering was extended using same projectile ( ${}^7\text{Li}$ ) but with somewhat heavier mass target nuclei ( ${}^{159}\text{Tb}$ ) in order to observe TA/BTA.

The study of fusion barrier distribution is also widely used to characterize the importance of various reaction channels coupling. Quasi-elastic channel can be termed as a sum of elastic, inelastic, transfer and breakup channels, which is complementary to complete fusion channel. In the literature, many measurements have been reported using quasi-elastic back angle scattering data [25, 39, 40, 41]. In one of the recent measurements on reaction of  ${}^6\text{Li}$  with  ${}^{232}\text{Th}$ , the shift in height of the fusion barrier by the coupling effects has been observed [39]. Similarly, in Ref. [25] barrier distribution was extracted from excitation function of the quasi elastic scattering at a backward angle for weakly bound projectile  ${}^9\text{Be}$  on  ${}^{208}\text{Pb}$  target, where it is mentioned that quasi elastic scattering (QEL) is shifted to lower energy by 1.5 MeV. Therefore, a systematic study related to this energy shifts as a function of product of the target and projectile charge can provide further understanding on effect of breakup on fusion reaction channels.

## 1.6 Objectives of the study

- To obtain the elastic scattering angular distributions and fusion cross sections and their simultaneous investigation by CDCC-CRC formalism using FRESKO code to check the breakup and/or transfer coupling effects in the light mass system that is,  ${}^7\text{Li} + {}^{27}\text{Al}$ .
- To obtain the elastic scattering angular distributions and study the energy dependences of optical model potential parameters using Woods-Saxon form of potential for  ${}^7\text{Li} + {}^{159}\text{Tb}$  system. Also, to study the breakup coupling

effects on the elastic scattering angular distributions by CDCC calculation using FRESKO code for this system.

- To obtain the fusion barrier distributions from quasi-elastic scattering excitation functions and to compare with the one obtained from the fusion excitation functions. To carry out coupled channels calculations (CDCC-CRC) employing FRESKO code for  ${}^6,7\text{Li} + {}^{209}\text{Bi}$  systems.

With the above objectives, investigations have been carried out employing three different alternatives such as elastic scattering angular distribution, fusion cross-section and quasi-elastic scattering excitation function measurements, experimentally as well as theoretically. In details, simultaneous measurements for elastic and fusion channels have been carried out for  ${}^7\text{Li} + {}^{27}\text{Al}$  system. Threshold anomaly has been studied for  ${}^7\text{Li} + {}^{159}\text{Tb}$  system. Fusion barrier distributions have been extracted from the quasi-elastic scattering excitation functions for  ${}^6,7\text{Li} + {}^{209}\text{Bi}$  systems. Moreover, theoretical investigations on the experimental results have been carried out in terms of CDCC and CRC formalism using FRESKO code [42].

## 1.7 Plan of the Thesis

The present thesis has been organized into six chapters as given below:

**Chapter1** gives a brief introduction on heavy ion induced reaction studies. Also, the importance of nuclear reactions with the halo nuclei and radioactive ion beams(RIBs) and current results on vigorous study employing weakly bound nuclei have been discussed along with its applications. Also, the motivation and objectives of the present thesis are given at the end of this chapter. **Chapter2** describes the importance of the theoretical investigation. Different theoretical models used to describe the present experimental data also have been presented briefly. **Chapter3** presents simultaneous study on elastic scattering angular distribution and fusion cross section measurement for  ${}^7\text{Li} + {}^{27}\text{Al}$  reaction. The experimental technique for this measurement is also given. The results and conclusions from the

coupled channels calculation using FRESKO code, to explain present experimental data are briefly discussed. In **Chapter4**, elastic scattering angular distribution measurement for the reaction of  ${}^7\text{Li}$  with  ${}^{159}\text{Tb}$  is given along with the Optical model analysis. The Coupled channels calculations using FRESKO code, are also presented to study the effects of breakup coupling. A brief experimental setup and technique for this measurement is discussed. In **Chapter5**, detailed study on fusion barrier distributions in the reaction of  ${}^{6,7}\text{Li}$  with  ${}^{209}\text{Bi}$ , has been presented. Comparative study of fusion barrier distributions have been carried out, obtained using the quasi-elastic scattering and fusion cross section measurement for the present systems. Simple coupled channels calculations and continuum descritized channel calculations have been carried out and the corresponding results have been given to interpret the barrier distributions. Finally, **Chapter6**, presents the summary and conclusions of this work along with the future outlook.