Chapter 1

Introduction

In the year 1911, Rutherford's observation of the nucleus lay the groundwork for the modern world of *Nuclear physic*s. In successive years, uncovering of neutrons, the designing of accelerators, and numerous fundamental research work allowed the use of various probes thus aiding the growth of this mysterious field to be known. In these studies, a fundamental understanding of the structure of the nucleus and its dynamics was made accessible. The invention of a wide range of radiation detectors, resourceful accurate accelerators, fast electronics, and swift electronics operation has promoted the appreciation of the subject. And today this branch has an association with various disciplines of science and technology. Not only regarding the fundamental understanding of matter but also in social usages like nuclear energy, radio isotropic use for medical treatment, and archeological departments, nuclear importance is on flying wings. The ultimate aims of nuclear physics exist in investigating nature of nuclear interactions among nucleons as well generalize for a collection of nucleon systems, known as nuclear structure. The current scenario in nuclear physics is to explore feathery details of nuclear structure and behavior at extremes of energy, momentum, and temperature, as well as to extend the range of nuclei beyond the line of stability.

1.1 Heavy Ion Nuclear Reaction Mechanism

Information on the relative probability of different reactions provides hints to the problem of nuclear structure and serves as a testing ground for nuclear force theories. Any nuclear transmutation process can result in the excitation of state of the product nucleus, and further its decay can provide information regarding energy levels and decay schemes. Thus, nuclear reactions become of a core importance to scrutinize the nuclear structure and forces among the system of nucleons. However, studying heavy ion processes without using an accelerator facility is impossible since strong nuclear forces are only apparent when nucleons interact in a permitted range. Accelerators have made it possible to investigate heavy ion nuclear reactions at very high temperatures and angular momentum. Generally, a nuclear reaction with a projectile mass greater than helium (A>4) is a category of heavy ion nuclear reaction. The impact factor of given projectile incorporates a crucial involvement in deciding the type of interaction taking place. Figure 1.1 depicts the influence of the impact factor of an incoming projectile on the involvement of the target nucleus. The large impact factor is dominated by the Coulomb effect and processes like Rutherford scattering and Coulomb excitation may take place. When nuclear densities of projectile and target overlap then nuclear reaction take place and small overlaps take care of elastic/inelastic scattering or few nucleons transfer through direct reactions. For a small impact factor, complete nuclei overlap takes place and a compound nucleus can form. A nuclear reaction is depicted by the type x + X → Y + y or can be denoted to x (X, Y) y in condensed form. A projectile particle x strikes on target nucleus X to produce daughter nucleus Y and an ejectile y. The ejectile can be any elementary particle or γ-rays or any light nucleus for instance d, α-particle. This equation, however, does not encompass all aspects of interest response. More than one particle may crop up in just about all cases, or the ejectile particle may be identical to the incident particle. This theme can be clarified in figure 1.2.

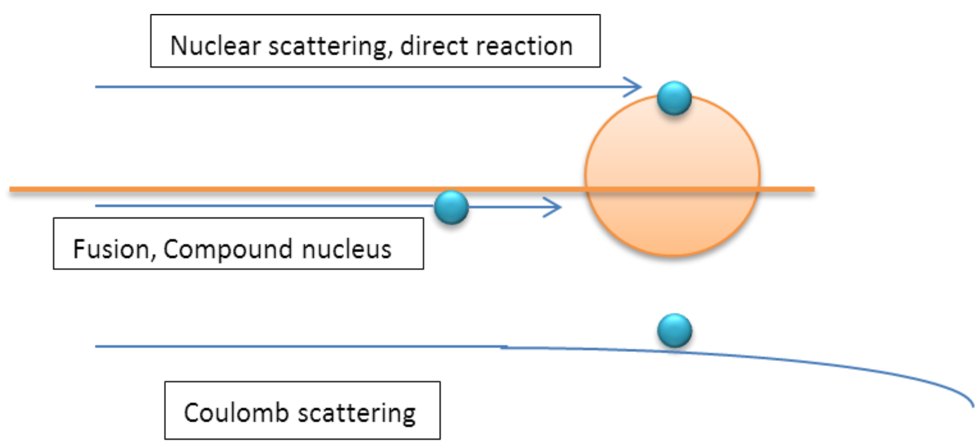

Figure 1.1: *The nuclear phenomenon takes place based on the impact factor of the incoming projectile. Schematic representation of involved processes based on impact factor.*

Two major classes of nuclear reactions according to time scale [1] are (i) *Direct nuclear reaction* (DR) where only a few nucleons take part and the remaining nucleons act as casual observer thus involving few degrees of freedom (ii) *Compound nuclear reaction* (CN) where incoming projectile completely unite with target nuclei to lose their identities and thus complete sharing of incoming energy is among all the nucleons before any nucleon gets ejected. The process is similar to evaporation from hot liquid. These sorts of reactions can populate continuum states of nuclei and these states have large excitation energy. Thus these reactions involve complex excitations involving many degrees of freedom. A detailed description of these categories of reactions is given below.

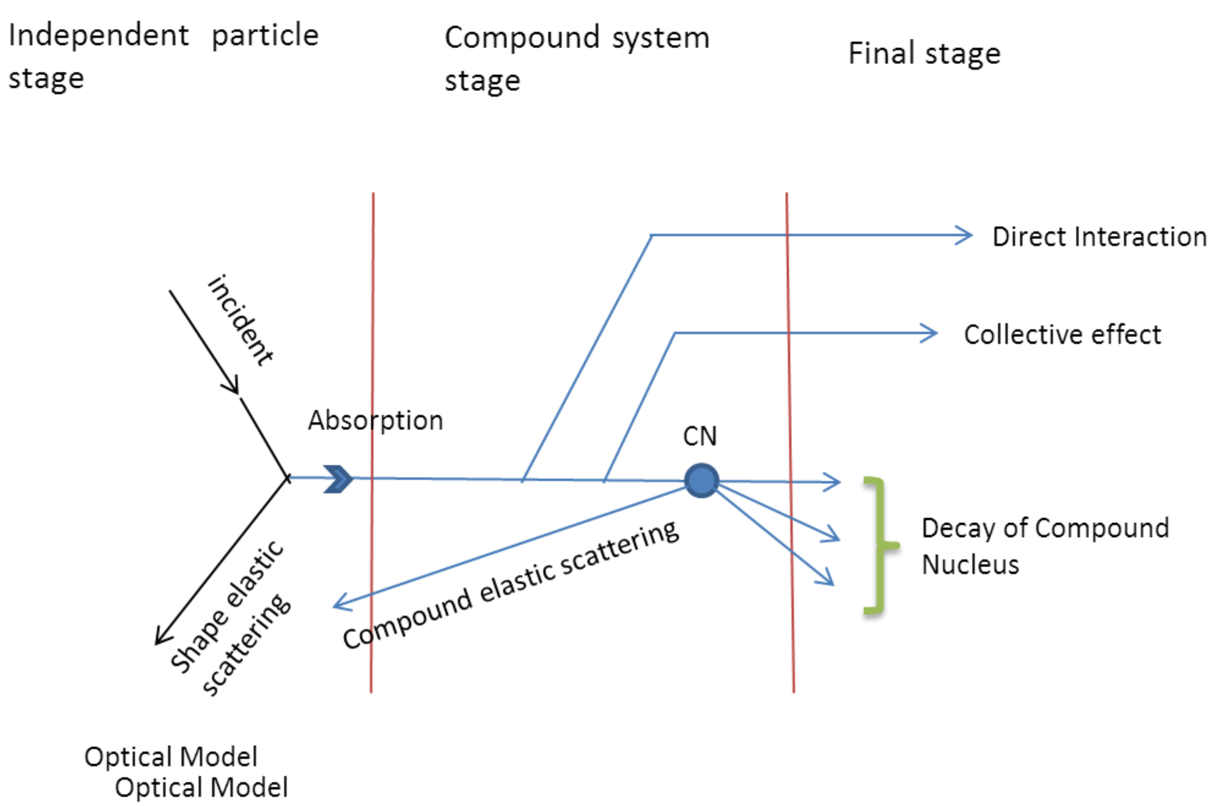

Figure 1.2: *Different stages of nuclear interaction when the projectile is bombarded on the target nucleus.*

[1] Direct Reaction: The time scale of direct reaction is 10^{-22} sec. and thus it is assumed that incoming projectile and outgoing ejectile hardly perturb other nucleons in the nuclear shells. Direct reactions typically skip the intermediate stage and move straight from the initial to the final partition. Direct reactions are very suitable for furnishing information about the association (overlap) of ground and particular excited state of target or projectile nucleus. Direct reactions are incorporating varieties of phenomena that are

(A) Elastic Scattering: Total kinetic energy of system (projectile + target) and interacting particles are same before and after the collision. Typically, Equation for elastic channel can be demonstrated as x + X → X + x. Even if some energy is transmitted from projectile to target, the internal or nuclear state of target does not change during elastic scattering. The importance of measuring elastic scattering arises from the fact that optical potential parameters may be derived from it.

(B) Inelastic Scattering: Typically, Equation 1 for inelastic channel can be demonstrated as x + X → X* + x'. The interacting particles are identical before and after the collision, but one or both of them may be excited, resulting in a change in the system's total kinetic energy (projectile + target). The relevance of studying inelastic scattering is that it gives information such as nuclear spin and excited state parity.

© **Transfer Reactions:** Typically, Equation 1 for the transfer channel can be demonstrated as x + X → Y + y. In a transfer reaction, when a projectile crosses over the target's perimeter, one or more nucleons get shifts between target and projectile.

(a) Pick-up: When a projectile gather one or more nucleon from the target nucleus, while passing through its periphery, the process is named a pick-up reaction.

Figure 1.3: *Schematic presentation of a transfer pick-up reaction.*

(b) Stripping: When a projectile hand over one or more nucleon to the target nucleus while passing through its periphery, the process named stripping reaction.

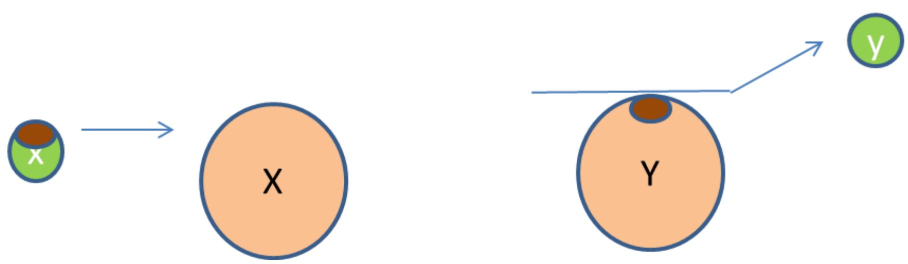

Figure 1.4: *Schematic presentation of a transfer stripping reaction*.

(c) Knock-Out: When a projectile hits a light nucleon from the target nucleus while passing through its periphery to establish three particles in the final partition, the process is named knock-out reaction. This is known as quasi-free scattering also as the projectile remains free before interacting with the target.

Figure 1.5: *Schematic presentation of a transfer knock-out reaction.*

(A) **Breakup Reaction:** The breakup reactions are known to occur with a typical collision time scale of 10^{-22} sec with the condition of impact parameter near the grazing distance. Consequently, breakup reactions may be categorized into direct or peripheral reactions. If a projectile possesses a low breakup threshold, it might disintegrate into its cluster constituents while advancing in the target nucleus field. This important aspect is crucial for weakly bound projectiles (^{6}Li, ^{7}Li, ^{9}Be). The broad description of this category is further covered under section 1.3.

[2] **Compound Nucleus Reaction:** Niels Bohr put forward the concept of compound nucleus [1,2] creation, proposing nuclear reaction as the decay of particles followed by a long lived intermediate stage lasting 10^{-15} sec. This intermediate state is highly excited as all incoming energy of the projectile is deposited to share among all nucleons. This way a heavy ion induced compound nucleus is hot and highly excited. This excited energy of the compound nucleus diminish by emitting particles like neutron, proton, α-particle, γ-rays, or fission fragments of medium mass nuclei as shown in figure 1.3. Thus two nuclei possess sizable overlap for small impact factor, a population of large number of states and thus situation favors to statistical distribution of properties (energy, entropy, temperature, etc).

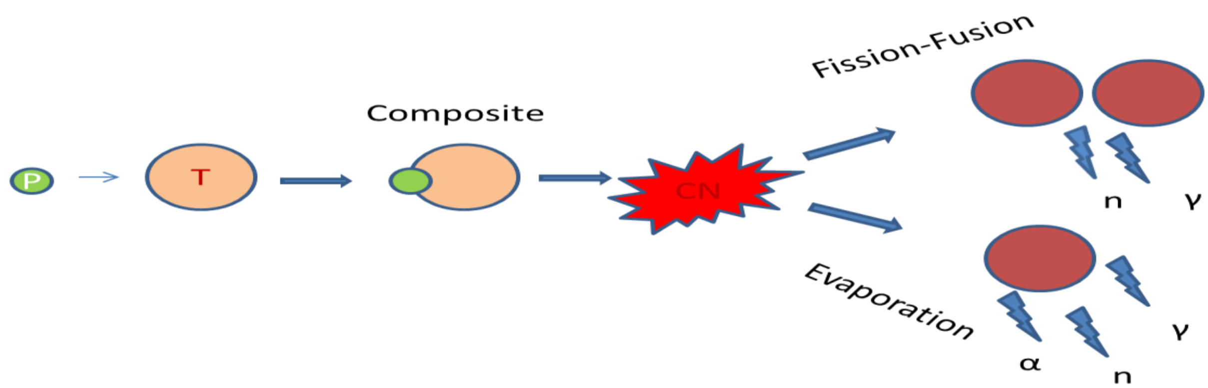

Figure 1.6: *Schematic representation of the formation and decay of Compound Nucleus (CN).*

Experimental difference between DR and CN reaction :

(1) Energy spectrum

The reaction mechanisms can be distinguished as outgoing particles have different energy distributions. For example, energy spectra of charge particles and neutrons are demonstrated in figure 1.7 when protons were incident on middle mass nuclei at bombarding energy around or slightly more of Coulomb barrier energy. The higher energy side contains discrete energy peaks and thus corresponds to elastic, inelastic, and transfer reactions and these categories can be separated on basis of their nature of interaction from each other by using specific detectors. The discreteness of energy is more visible for higher energy and the lower energy side has a lesser resolution of peaks. At very low energy the compound nucleus decay products show their dominance.

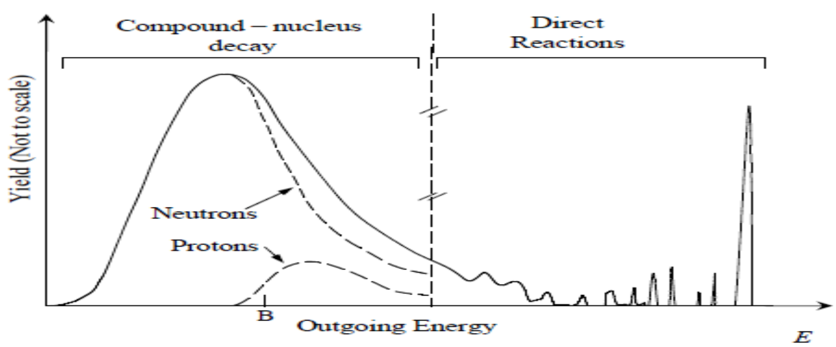

Figure 1.7: *Energy spectra for charge particles and neutrons. Figure is taken from J. S. Lilley, Nuclear Physics – Principles and applications (John Wiley and Sons Ltd.*

(2) Angular distribution of product

The direct reactions are peripheral collisions and thus most of energy and momentum of the incoming particle are taken away by an outgoing particle which results in forward peaking of the angular distribution spectrum. The wave nature particles can also commonly reflect in the angular distribution spectrum which gives interference phenomenon same as in optics. Furthermore, angular distribution of evaporated particles for CN is isotropic and symmetric at about 90°.

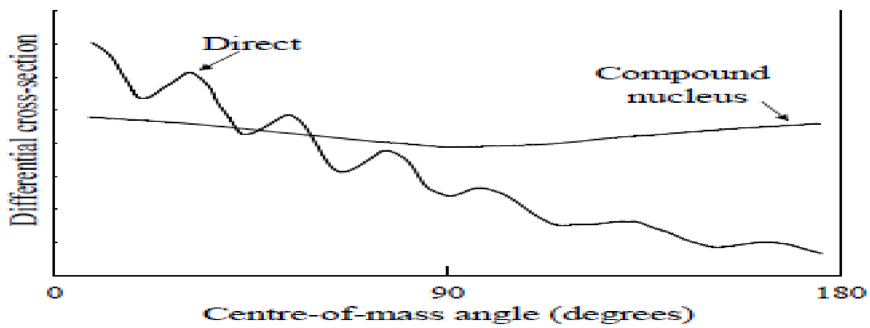

Figure 1.8: *Differential cross section for an outgoing particle for direct reaction and decay of compound nucleus.*

1.2 Interesting features of Weakly Bound Nuclei and their Breakup Reactions:

Weakly bound nuclei are those which have lesser binding energy in comparison to tightly bound nuclei. The B.E./nucleon of tightly bound nuclei varies from 6 to 8 MeV. For weakly bound nuclei, breakup threshold (for eg. ^{6}Li, ^{7}Li, and ^{9}Be) ranges ~1.5 MeV- 2.5 MeV. Stable weakly bound nuclei viz. ^{6}Li, ^{7}Li, ^{9}Be and unstable weakly bound nuclei like ^{6}He are predominantly in α+x cluster structure and possess low breakup threshold as depicted in figure 1.9. Apart from α+x cluster, these nuclei can exhibit another cluster forms also as shown.

It's also conceivable that revolving protons or neutrons form a ‘halo’ around the core nucleus, increasing the total nucleus radius beyond what the liquid drop model predicts; such nuclei are known as *"Halo nuclei"*. The half-life of these nuclei is measured in milliseconds. ^{6}He, for example, has two neutron haloes and decays to ^{6}Li (^{6}He→^{6}Li) with a half-life of 806 milliseconds. In a table of nuclei, halo nuclei usually create a neutron drip line and a proton drip line. Other halo nuclei are ^{11}Li, ^{11,14}Be, ^{8,17}B, etc. Sometimes halo nuclei are named "*exotic nuclei*" or *"Borromean nuclei"* too. As an example, two neutron halos are called Borromean in the sense that two neutrons and core nuclei are linked to each other but they share no link. Figure 1.11 shows a part of the Segre chart containing this group of nuclei. The figure was taken from reference [4]. The high-tech availability of accelerators and detectors has enabled researchers to investigate the characteristics of these nuclei. Despite this, stable ion beams (^{6}Li, ^{7}Li, and ^{9}Be) are very straightforward to examine due to their widespread availability.

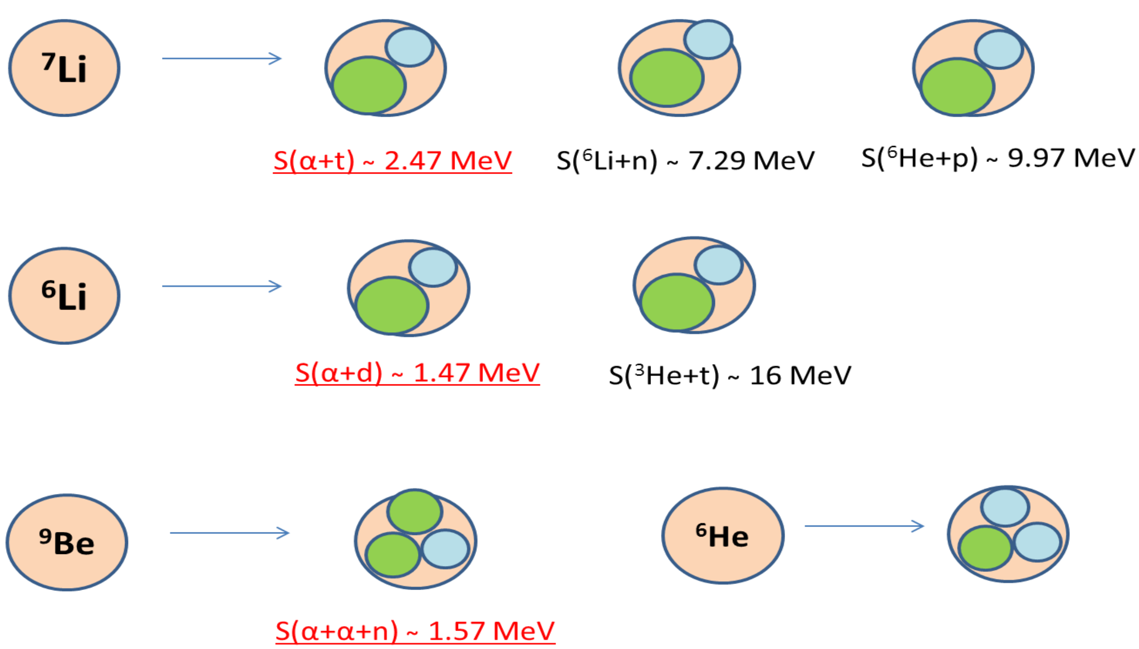

Figure 1.9: *Cluster structure in some weakly bound stable and unstable nuclei.*

example, has two neutron haloes and decays to ^{6}Li ($^{6}He \rightarrow ^{6}Li$) with a half-life of 806 milliseconds. In a table of nuclei, halo nuclei usually create a neutron drip line and a proton drip line. Other halo nuclei are ^{11}Li, $^{11,14}Be$, $^{8,17}B$, etc. Sometimes halo nuclei are named "*exotic nuclei"* or *"Borromean nuclei"* too. As an example, two neutron halos are called Borromean in the sense that two neutrons and core nuclei are linked to each other but they share no link. Figure 1.11 shows a part of the Segre chart containing this group of nuclei. The figure was taken from reference [4]. The high-tech availability of accelerators and detectors has enabled researchers to investigate the characteristics of these nuclei. Despite this, stable ion beams (^{6}Li, ^{7}Li, and ^{9}Be) are very straightforward to examine due to their widespread availability.

The breakup reactions are known to occur with a typical collision time scale of 10^{-22} sec with the condition of impact parameter near the grazing distance. When some weakly bound projectile (WBP) enters in territory of a target nucleus then it may breakup into its cluster constituents either directly or get excited to resonance levels above breakup threshold followed by breakup. This phenomenon leads to an effective impression on observables such as α-production, fusion cross section, transfer reactions, and other reaction channels. When a WBP interacts with a target nucleus then either it can directly fuses with the target or it can undergo to breakup into its constituents followed by 'sequential complete fusion (SCF)' or 'incomplete fusion (ICF)' or just elastic breakup. An illustrative example of these situations is presented in figure 1.10. WBP $^{6}Li \rightarrow \alpha + d$ is considered as an example and consequent reaction possibilities of breakup are shown.

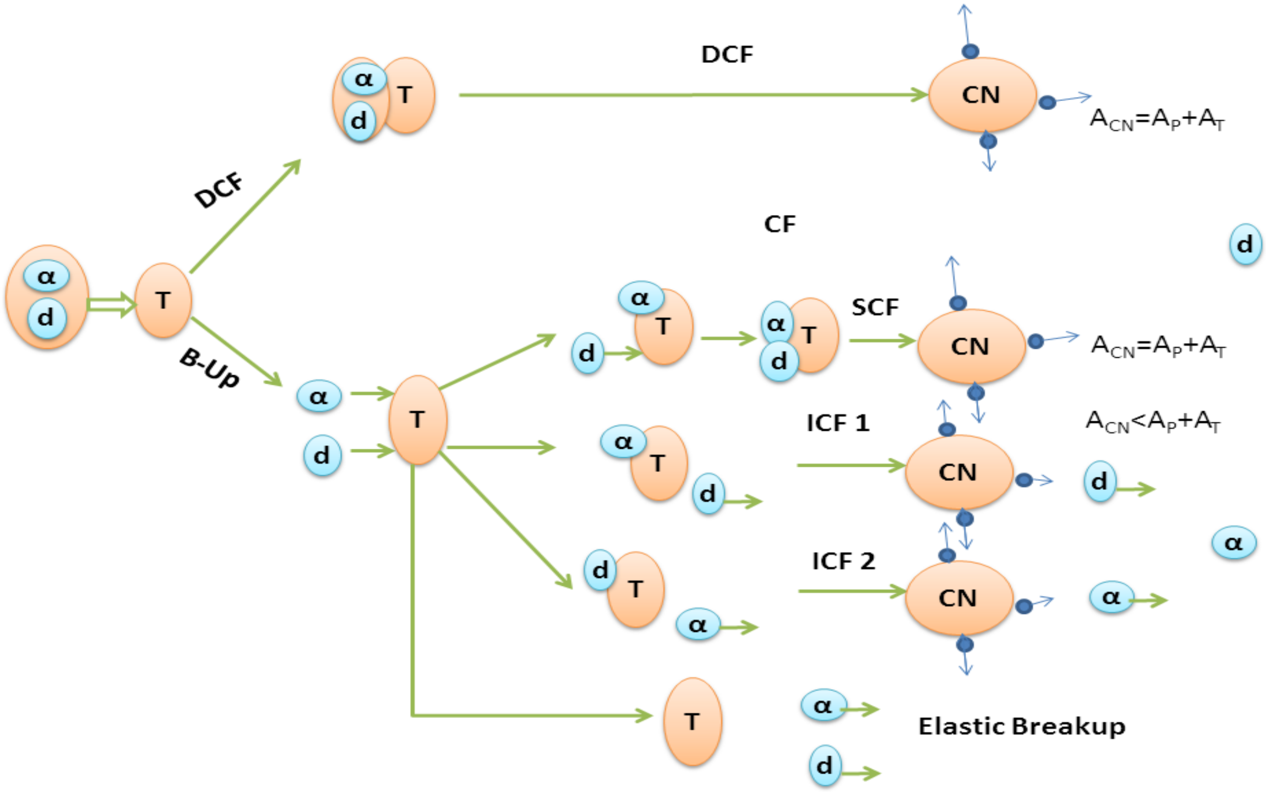

Figure 1.10: *The detailing of the process when weakly bound projectile nuclei interact with target nuclei. A typical example taken over here is WBP ^{6}Li (α+d).*

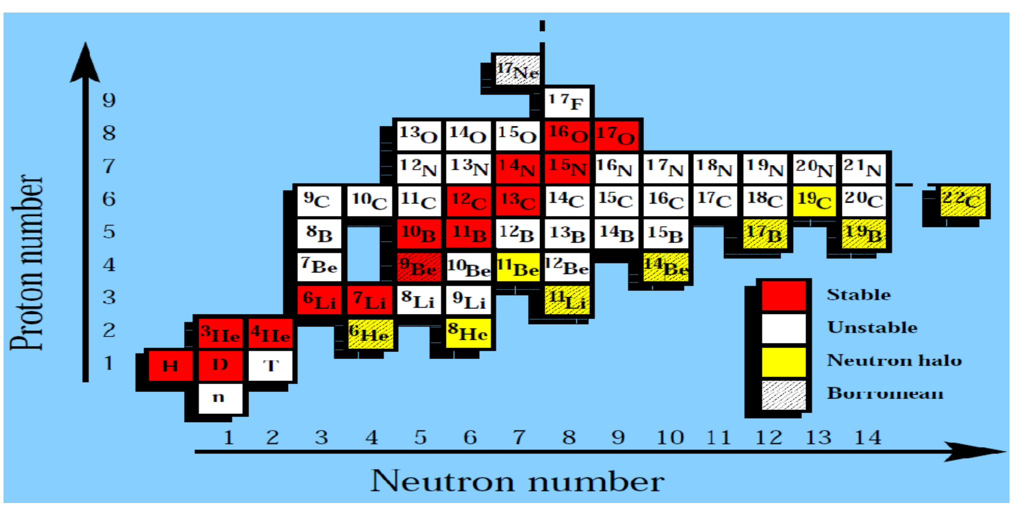

Figure 1.11: *Part of Segre chart containing weakly bound category of nuclei.*

1.3 General Motivation for Study

1.3.1 Study of Elastic Scattering

The high-tech availability of accelerators and detectors has enabled researchers to investigate the characteristics of these nuclei. The properties to be looked at while studying weakly bounded projectile are (i) Elastic Scattering, where optical potential parameters are extracted and their dependence on energy is depicted in terms of 'Threshold Anomaly (TA)' / 'Breakup Threshold Anomaly (BTA)' (ii) Inclusive alpha, where the origin of large inclusive alpha (alpha from all the possible channels) cross section gives clue about dynamics of the weakly bounded projectile (iii) Complete fusion, the suppression/ amplification of fusion cross section contrast to theoretical calculations or tightly bound projectile.

Elastic scattering angular distribution measurement becomes very effective way while the breakup coupling effect study is regarded. One can always investigate the energy dependence of potential parameters. Different types of nuclei demonstrate different signatures for potential parameters around Coulomb barrier assigned by given behavior. The strongly bound systems exhibits Threshold Anomaly (TA) near barrier to the energy dependent phenomenological optical potential parameters [6, 7, 8]. Whereas the imaginary component depicts the rapid closure of other channels, the real part exhibits a corresponding bell-shaped peak around that energy range. The real potential $V = V0 + \Delta V$ has energy dependent ΔV part which is called polarization potential. The attractive polarization potential is in care of displaying coupling of different inelastic channels with elastic channels, resulting in an overall amplification of real component of potential to peak near barrier. Such a trend is demonstrated in figure 1.12**.** TA, on the other hand, is not a universal characteristic in the WBP collision. The breakup cross section come across as of being extremely significant below the Coulomb barrier in such circumstances, as imaginary segment refuses to drop in the barrier area and displays an elevation that may be constant even when the bombarding energy lowers. This resulted in an enhancement in the imaginary portion of potential, which also is escorted by a dip in the real part. Breakup Threshold Anomaly is the name for this unusual dependency (BTA) [9, 11, 12, 13, 14, 15]. This time repulsive polarization potential is evolved by coupling other channels with elastic channels. This trend is demonstrated in figure 1.13**.** At all incoming projectile energies, the dispersion relation [10] guides towards investigation the correlation between real and imaginary components. When it comes to recreating elastic scattering cross sections, an effective interaction is introduced. This interprets for all coupling effects and therefore lessens a multi-body problem to a single-body complication. If V and W are real and imaginary components of potential then,

$$U(r;E) = V(r;E) + i\,W(r;E) \qquad (1.1)$$

Also we know $$V(r;E) = V0(r;E) + \Delta V(r;E) \qquad (1.2)$$

V and W are connected by dispersion relation :

$$\Delta V(r,E) = \frac{P}{\pi}\int_0^{\infty} \frac{W(r,E')}{E'-E}\, dE' \qquad (1.3)$$

It should be noticed that V(r, E) is an attractive polarization potential. At low energy W(r; E0) depicts an imaginary potential with minor impact on V(r, E). The phenomenological optical model potentials were derived at all energies and then dispersion relation at the radius of sensitivity as energy function was delimited. The imaginary potential may be thought of as a series of linear segments based on experimental data, followed by a numerical computation of equation (1.3) to generate the real component.

As far as tightly bound nuclei are concerned, elastic and inelastic channels possess strong coupling within and thus Threshold Anomaly (TA) is the established behavior for them. Moreover, the threshold behavior of stable weakly bound projectiles nearby Coulomb barrier energy has exhibited diversity in observations. For instance, in the case of ^{6}Li, nearly every mass range system has been reported to show Breakup Threshold Anomaly (BTA) behavior. Some of the systems are ^{27}Al [11], ^{80}Se [12], ^{112,116}Sn [13], ^{144}Sm [14], ^{208}Pb [15]. In the case of ^{28}Si [16, 17], there exists a contradiction in the result. But still, on the lighter mass side, more experiments are required to make a transparent conclusion. For weakly bound projectile ^{7}Li, a variety of discrepancies can be seen while moving from the lighter to the heavier mass range. No TA was observed for ^{7}Li with lighter medium mass ^{27}Al [18, 19], ^{28}Si [20] while just a little heavier ^{59}Co [21], ^{80}Se [22] have reported TA. Moving towards medium heavy mass viz. ^{144}Sm [23], ^{159}Tb [24] TA is not observed but for ^{138}Ba [25] which is in the same mass range show TA behavior. The heavy mass targets like ^{7}Li on ^{208}Pb [26] and ^{232}Th [27] have confirmed the appearance of TA. Nevertheless, apart from these nuclei, light weakly bound radioactive projectiles are rather common in basic configuration of presence either absence of TA/BTA. Studies on various targets have been measured using neutron-rich ^{6}He, proton-rich ^{8}B, and ^{7}Be. However, the difficulty of such a study, which is exacerbated by the restricted beam intensity and purity, influences the major findings.

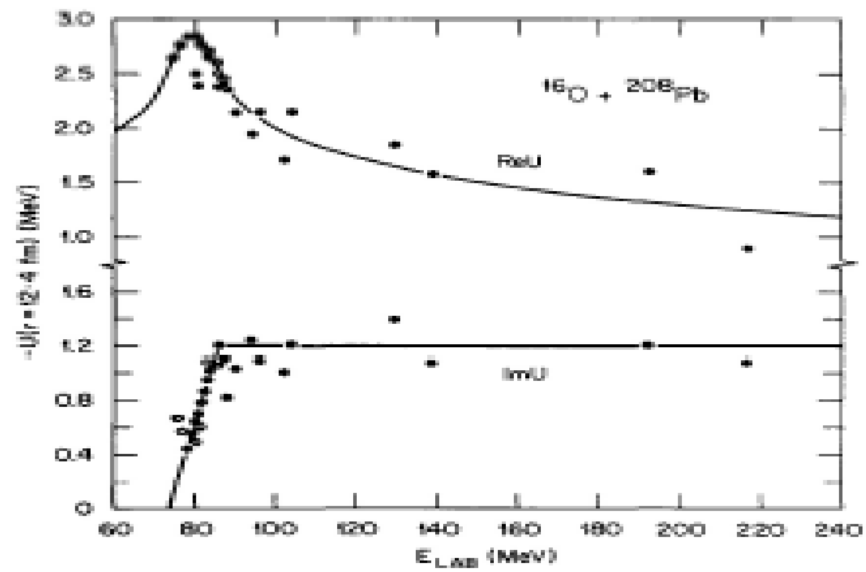

Figure 1.12*: Typical example of TA behavior for system $^{16}O+ {}^{208}Pb$ [6].*

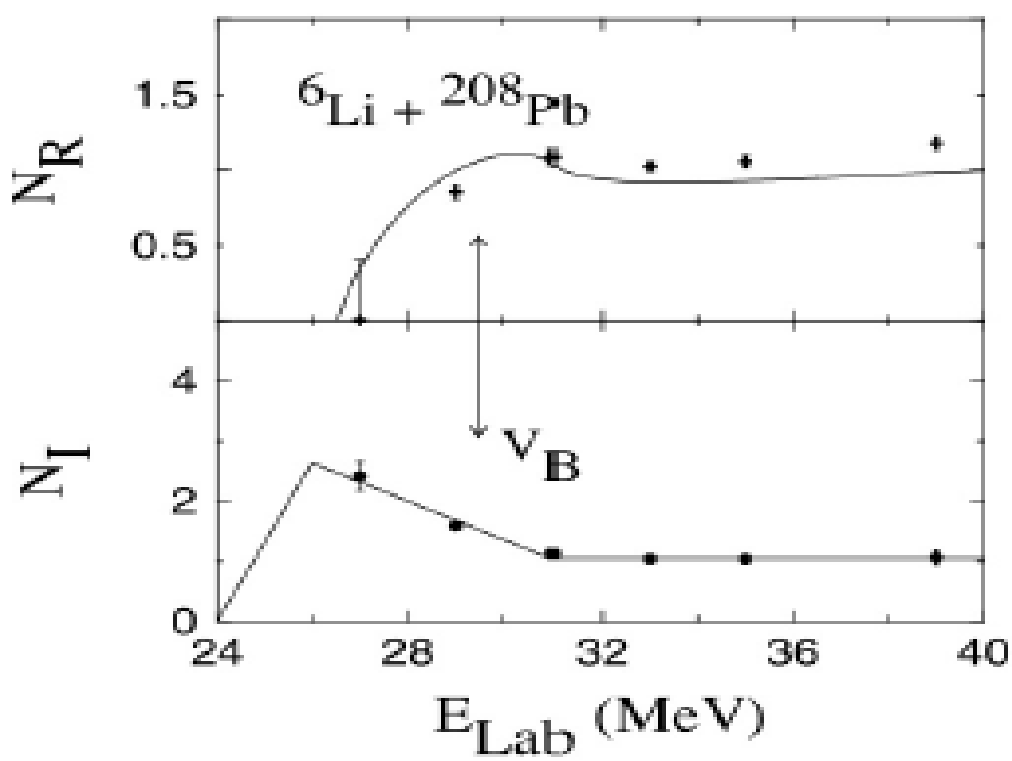

Figure 1.13: *Typical example of BTA behavior for system $^{6}Li + {}^{208}Pb$ [9].*

1.3.2 Study of Inclusive Alpha Production

The internal degrees of freedom for heavy ion reactions play a vital role nearby the Coulomb barrier region which is revealed through observations of (i) TA in optical potential [11-15] and (ii) an enhancement/suppression in fusion cross section [28-30]. These observations are clarified in terms of coupling to other reaction channels and manifestation of weakly bound projectiles breakup as a significant channel. Thus channels like transfer, the inelastic excitation may enhance the fusion cross section but channels like breakup may reduce the overall flux for fusion. Inclusive and exclusive studies for alpha-production manifest that a large alpha cross section is a linked phenomenon with the breakup and transfer channels [31, 32].

Reactions incorporating WBP with cluster structure ‘α+x’ encourage substantial alpha production cross sections [33-35]. Numerous attempts have been performed to understand the large inclusive alpha production compared to other fragments, but a full understanding of the topic is yet to be clarified [36]. The high alpha yields indicate that deuteron transfer and breakup fusion is preferable to alpha production and that other reaction channels supporting the dominant production are more likely to exist. In studies of the alpha spectrum with exclusive measurements transfer channel is paramount [37] whereas breakup fusion plays a vital role in others [38]. For ^{6}Li almost 50% contribution to alpha was concluded from neutron transfer [39]. Several reports [31-38] exhibit inclusive and exclusive measurements to clarify the contribution of various reaction channels for inclusive alpha-production but this is still an open question.

1.4 Objectives of Study:

The following studies justify to the purpose;

- The elastic scattering studies for system $^{6}Li+^{51}V$. Data analysis using different potentials and simultaneous description of data using Continuum Discretized Coupled Channel calculations (CDCC). Investigation of potential behavior in that of double folding framework from density distribution to understand anomaly. Systematics of all available measurements to generalize threshold behavior and cross section for ^{6}Li.

- The elastic scattering angular distribution study for $^{7}Li+^{92,100}Mo$ systems. Analysis of data in Wood Saxon potential and São-Paulo potential frameworks. Threshold anomaly behavior in both of these frameworks. Theoretical description of data with CDCC calculations. A systematic behavior study with present measurements also is to be done.

- Inclusive alpha cross section studies for system $^{6}Li+^{51}V$. Elastic scattering studies and other direct channels like transfer reactions are studied thoroughly. Theoretical calculations like CRC calculations for transfer reactions and CDCC for the breakup and elastic scattering produce the experimental measurements in good agreement.

- Elastic scattering angular distribution studies for system $^{6}Li+^{100}Mo$. A systematic and predictable theoretical development requires a huge collection of experimental data.

Analysis of data in optical potential frameworks. Threshold anomaly behavior in this framework.

1.5 Scheme of Thesis:

The present thesis has been assembled into seven chapters as given below:

Chapter 1 avails introductory description about the nuclear reactions and their mechanism. A broad discussion about different types associates during a nuclear reaction is presented. The influence of projectile selection like heavy ion projectile or weakly bound projectile has been discussed to prepare the base of the thesis. The chapter takes care of a broad discussion of weakly bound projectiles like ^{6,7}Li, ^{9}Be, etc. and their role in understanding their special impression on the mechanism of reaction taking place. The objective of the write up is established.

Chapter 2 recounts the significance of an accelerator in a nuclear reaction, its construction detailing, and the practical implementation of its usage for research purposes. Further, the necessity of a detector and its fundamental role during the interaction of a charged particle with matter is explained in detail. Apart from experimental necessities, theoretical tools for calculations are also described. In this view, nuclear reaction models and potential undertaken for analysis are discussed in detail. To look over the consistency of results, different kind of models and potentials are utilized independently. A detailed discussion of theoretical calculations supporting the understanding of the objective of the thesis like energy dependence of potential, the breakup of the projectile, the reaction mechanism of various channels, etc. is presented in broad.

Chapter 3 narrates the elastic scattering studies for system ^{6}Li+^{51}V. The experimental details followed by data analysis using different potentials and simultaneous description of data using Continuum Discretized Coupled Channel calculations (CDCC) is discussed. Study of potential behavior in the double folding framework from density distribution to understand anomaly. Systematics of all available measurements to generalize threshold behavior and cross section for ^{6}Li is shown.

Chapter 4 details broadly on the measurements of angular distribution and energy spectrums of the alpha and deuteron through various reaction channels viz. breakup, transfer, and incomplete fusion are studied to investigate their relative contributions to a reaction.

Chapter 5 details the elastic scattering angular distribution study for ^{7}Li+^{92,100}Mo systems. Analysis of data in Wood Saxon potential and São-Paulo potential frameworks. Threshold anomaly behavior in both of these frameworks. Theoretical description of data with CDCC calculations. A systematic behavior study with present measurements also is to be done. Some quasielastic barrier distribution studies are done. For more clear picture we are waiting for another beam time. A comparative study is performed for the fusion cross section and total reaction cross section to understand effect of breakup on fusion.

Chapter 6 presents the elastic scattering studies for system ^{6}Li+^{100}Mo. Data analysis using optical model potential with description of data by SFRESCO fitting. Study of the energy dependence of potential parameters and to understand anomaly nearby barrier region.

Chapter 7 depicts a brief summary of research work carried out in the present thesis along with the future outlooks.

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