



## Chapter – 1

### *Introduction*

*Nucleus*. A small dense region of an atom, in its centre consisting of nucleons; neutrons and protons. It has a size of orders of a few Fermi ( $\sim 10^{-15}\text{m}$ ).

The etymology of the term nucleus is from 1704 meaning “kernel of a nut”. In 1844, Michael Faraday used the term to refer to the “central part of an atom”. The modern atomic meaning was proposed by Ernest Rutherford in 1911 [1] and the adoption of the term “Nucleus” to atomic theory was done in 1916 when Gilbert N Lewis stated in his article “The atom and the molecule” that atom is composed of the kernel and an outer most shell [2]. Nucleus is a fascination world which drove the scientists all over, since the early 20<sup>th</sup> century and kept on surprising every now and then with its rich and variety of phenomenon.

## 1. Introduction

The atomic nucleus is a fascinating many-body system bound by strong interaction. The common theme for the whole field of nuclear structure is the problem of understanding the effective N - N force, which provides the wide variety of phenomena observed in nuclear physics. Many features of this effective interaction, such as short range, strong dependence on isospin and relative momenta of the interacting nucleons, have been extracted from experimental data available near the stability line.

The combined effect of the forces between pairs of nucleons in a finite nucleus can often be described in terms of a ‘mean field’. The complex motion of a nucleon under the influence of all other nucleons is approximated by a one-body potential. The primary information about the nature of the mean field in a nucleus comes from studying the properties of its excited states. A non-spherical mean field gives rise to excited states that are rotational in nature while a spherical potential can lead to both single-particle and vibrational states.

The nature of the mean field is fairly well understood for nuclei near their ground state. Nuclei near doubly-closed shell show behaviour characteristic of a spherical mean field while mid-shell nuclei show rotational behaviour. Due to the complex interplay between different degrees of freedom, the mean field itself is a function of excitation energy and spin. The population of sequences of nuclear states in the  $\gamma$ -decay of highly excited nuclei formed by heavy-ion fusion evaporation reactions has revealed the existence of a number of nuclear phenomena at high angular momenta, namely

backbending or bandcrossing, bands based on different nucleon configuration, shape changes as a function of increase in angular momentum and rotational frequency, shape coexistence, shape polarization, band termination, exotic shapes in nuclei – superdeformation, triaxial shapes, magnetic rotation, signature splitting, signature inversion etc. Understanding these exotic phenomena in terms of the basic N - N forces is a major challenge to the physicist.

One of the current major objectives for studying nuclear physics is to explore the “frontiers of nuclear structure”. For heavy nuclei, the frontiers are defined by the extremes of (i) N/Z ratio corresponding to the structures of nuclei close to the drip lines (ii) limits of mass and charge exploring the super-heavies and (iii) limits of angular momentum. One of the outstanding challenges in nuclear structure is to understand this third degree of freedom that governs the nature of nuclear collective excitations.

## 1.1. Nuclear Reactions and their Classification

### 1.1.1. Nuclear Fusion

Fusion may be defined as an amalgamation of the projectile and the target to form a compound nucleus such that the charge and mass of the compound nucleus formed can be described by Eq<sup>n</sup> 1.1.

$$(A_c, Z_c) = (A_1 + A_2, Z_1 + Z_2), \quad (1.1)$$

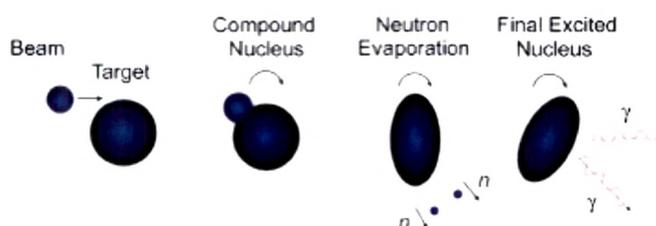


Figure 1.1: The main stages involved in a nuclear fusion reaction.

In this equation the right hand side stands for a state of the system, which is completely characterized by its total mass, charge, energy, and angular momentum and has reached equilibrium with respect to all other internal degrees of freedom [3]. In general, the compound nucleus is initially in a highly excited state due to the excitation

energy. This compound nucleus decays via particle emission [4] or fission [5] and  $\gamma$ -ray emission as illustrated in Fig. 1.1. In light nuclei, with  $Z \leq 70$ , the probability of fission is typically so small that all decays proceed via particle emission [5]. This particle emission is often referred as particle evaporation. The evaporated particles are predominantly neutrons, and also protons and  $\alpha$ -particles. This decay mode results in a nucleus, dubbed as the evaporation residue.

### 1.1.2. Break-up Reaction

The projectile break-up processes are symbolically written as



where, 'A' denotes a target nucleus while 'a' is a composite projectile nucleus composed of subunit particles b, c,... which are either nucleons or their clusters. When the target nucleus 'A' is left in its ground state, the process is called an elastic break-up, while if 'A' is left in one of the excited states ( $A^*$ ), it is called an inelastic break-up. If the ground state of the projectile nucleus has a well developed cluster structure, the projectile break-up into relevant clusters will be one of the most favourable reaction processes in nucleus – nucleus collisions induced by projectile. Thus, the break-up process is closely related to the cluster structure of the projectile nucleus and the study of the nuclear break-up provides valuable information on the nuclear cluster structure. Conversely, a precise knowledge of the nuclear cluster structure is essential to study the reaction mechanism relevant to the break-up process [6].

### 1.1.3. Compound Nucleus Reaction

When two nuclear systems collide, it forms a highly excited compound system (Fig. 1.2). This is called Fusion when two heavy ions collide. The composite system stays together sufficiently long for its excitation energy to be shared more or less uniformly by all its constituent nucleons. If a nucleon or a group of nucleons has got sufficient energy localised for them to escape the compound nucleus, then it is called the decay of compound nucleus. Schematically,



If sufficient excitation energy remains in  $D^*$ , further particle emissions may occur. Otherwise it will de-excite via  $\beta$ - or  $\gamma$ -decay. Because of the time taken between

formation and decay, and the many complicated nucleon motions that take place during the period, the system  $C^*$  may be said to have lost memory of the particular channel  $A + a$  by which it was formed, and the probabilities of the various decay modes  $B + b$  will be independent of each other and of the entrance channel.

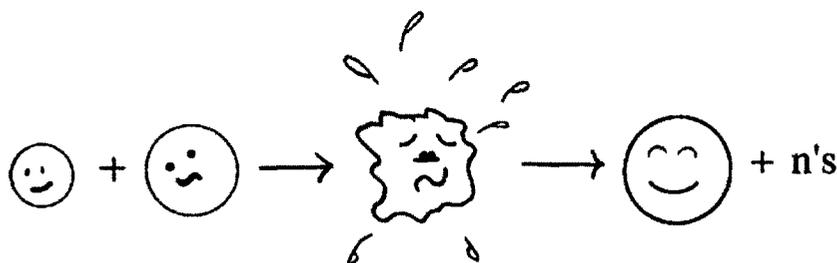


Figure 1.2: Schematic diagram showing compound nucleus Reaction.

#### 1.1.4. Direct Reactions

In direct reactions, unlike the above CN (Compound Nucleus) reaction, the two systems involved may make just glancing contact and immediately separate. Their internal states may be unchanged (elastic scattering), one (or both) may be excited by the contact (inelastic scattering) or one or a few nucleons may be transferred across from one nucleus to the other (transfer reaction). These reactions occur quickly and proceed directly from initial to final states without forming an intermediate compound state. These types of reactions are also called peripheral reactions. Clearly then we will not find any sort of independence between the entrance and exit channels. Pick-up and transfer reactions are the two important aspects of direct reactions, which are important for the population of the desired residue under the required conditions of energy and angular momentum [7]. Some of the types of reactions are shown in Fig. 1.3. and its description is given below.

##### *a. Elastic Scattering*

Elastic scattering is defined to be a collision in which the colliding particles only change their direction. In this reaction no kinetic energy of the projectile is used to take the target into an excited state. The projectile and the target remain in their ground states.

##### *b. Inelastic Scattering*

Inelastic scattering differs from elastic scattering in that the target nucleus is raised to an excited state as a result of the collision. Physically the projectile only touches the target

nucleus, or it may enter the nucleus and exit at a reduced energy. When the excited target nucleus returns to its ground state, the excess energy is released by the emission of particles like  $\gamma$ -rays.

**c. Transfer Reactions**

In transfer reactions, when the projectile passes over the periphery of the target one or more nucleons are transferred between the projectile and the target, such as an incoming deuteron turning into an outgoing proton or neutron, thereby adding some nucleons to the target  $X$  to form a nucleus,  $Y$ .

**d. Quasielastic Scattering**

In quasielastic scattering the projectile loses a moderate amount of energy and exchanges a few nucleons with the target nucleus. Quasielastic reactions are assumed to correspond to collisions in which the surfaces of the two ions have just been in a grazing contact. However, in this study, quasielastic will refer to the sum of all the elastic scattering, inelastic scattering and transfer reactions.

**e. Deep Inelastic**

This reaction entails substantial damping of kinetic energy and mass exchange. The larger fragments are highly deformed and excited while retaining partial memory of “target” and “projectile” masses and charges [8]. This process takes place at energies above the Coulomb barrier.

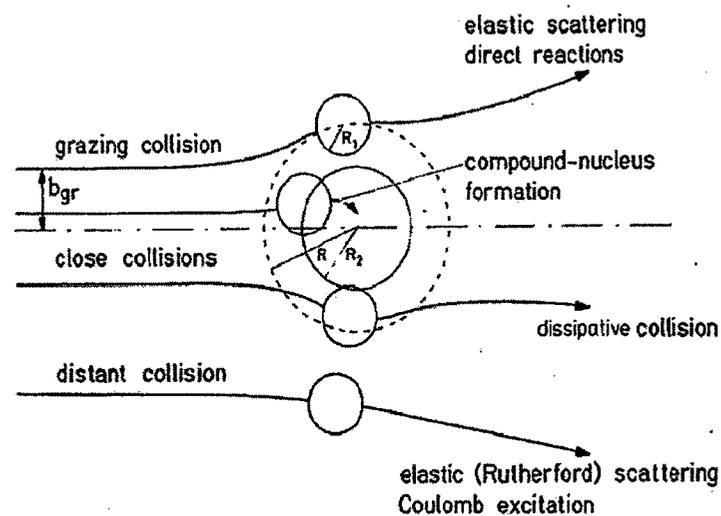


Figure 1.3: Distant, grazing and close collisions in the classical picture of heavy ion collisions [9].

## 1.2. Nuclear Structure and Gamma Spectroscopy

When the nuclei absorb excitation energy and angular momentum, they become excited and some changes in their intrinsic structure can occur. An excited nuclear state has particular properties (such as energy, angular momentum etc.), which can be experimentally measured and thus it becomes possible to deduce the changes in the nuclear structure. The excited states usually live for a short time (typically in the pico second (ps) range) and decay most often by emitting  $\gamma$ -rays. These  $\gamma$ -rays are detected and studied (gamma ray spectroscopy) in order to determine the properties of the excited states. The gamma rays carry information about the nuclear transition from the initial to the final level (Fig. 1.4) only, such as the amount of energy, angular momentum, parity etc. that is taken away. Thus in order to deduce the absolute values of the excitation energy, angular momentum etc. of the initial level, we need to know the absolute values for these quantities for the final levels.

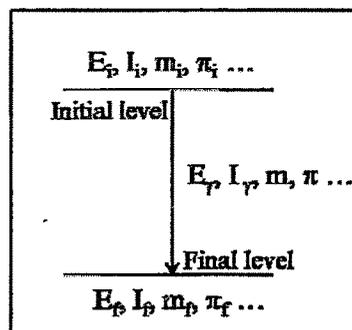


Figure 1.4:  $\gamma$ -Decay from initial to final level.

### 1.2.1. Nuclei at High Spins

When one thinks of angular momentum it is probably in terms of rotation of classical bodies. Nuclei are much more complex and interesting than classical rotors. They have important quantal aspects and further are finite systems, being composed of a rather small number of nucleons. This means that there are some restrictions on rotation and there are also important single particle or non-collective effects in nuclei, as well as a continuous variation between collective and non-collective properties. At one limit, the nucleons act coherently and collective bands develop that follow the  $I(I+1)$  rotational pattern to within a percent or two and have transition probabilities 200 times larger than a single particle would have; at the other limit, a few individual nucleons may carry all the angular

momentum of a high spin state. Between these limits we find sometimes a complex behavior and other times a co-existence of this simpler limiting behavior. The study of nuclei at high angular momenta can be cast into the form of understanding first these two limits themselves, and then the interplay between them as the spin increases

It is not difficult to trace the development of these two limiting situations. Single particle angular momentum was implied immediately by the shell model of nuclei which was conceived in the 1930's [10], but bloomed only after 1949 [11] with the recognition of the importance of spin-orbit splitting. It is, in principle, straight forward to align the angular momenta of many particles to make a high-spin state but reasonably pure shell-model (non-collective) states with more than three or four aligned particles (and spins higher than 10 or  $12\hbar$ ) are not so common.

Rotation of nuclei was proposed by Bohr [12, 13], based on the understanding that such a model was required by the existence of strongly deformed shapes. The art of calculating nuclear potential energy surfaces as a function of spin and shape parameters has been refined many times, using modified harmonic oscillator, Wood-Saxon, and, most recently, Hartree-Fock shell model potentials, all of which generally give reasonable agreement with the shapes that are observed. The way to connect the shell model structure to a collective moment of inertia, by cranking the potential was envisioned in 1954 [14]. The pairing correlations introduce strong non-rotational components into the flow pattern of nuclei, and thus reduce the moment of inertia [15, 16]. Recently it has been possible to identify the reduction of the pairing correlations with increasing spin, and the rise of the moment of inertia toward the originally predicted rigid-body value.

It was, of course, recognized that there was likely to be a full range of behavior between these limits. For low-spins the relevant region of "vibrational-like" nuclei has resisted a simple and satisfying treatment, and is still an area of intense study. In the higher spin range this problem came into focus in 1971 when a discontinuity (called back-bending) was observed in several rotational bands at spins around  $20\hbar$ . This behavior has been found to be due to the breaking of high- $j$  particles, and each aligning its angular momentum directly with the collective one generated by remaining particles. These rotational nuclei are clearly taking a step toward the non-collective limit.

Above the yrast line moving up in energy and temperature, new classes of phenomena may be explored. Examples include the quasi-continuum and rotational damping, shape and pairing phase transitions, the goal of complete spectroscopy, giant

resonances, the melting of shell structure and the transition from order to chaos. The yrast line connects the states with the lowest energy for each angular momentum value. Consequently no states exist below this line. Thus the spectroscopy of such "dizzy" nuclei has opened up several new dimensions and revealed interesting nuclear properties. The prominent role has been played by the heavy-ion induced fusion reactions in exploring the various nuclear phenomena at such high angular momentum.

### 1.2.2. Methods of Populating Excited States

In studying excited states of nuclei, the primary observables are the excitation energy, spin, and parity of the states. In addition, the wave functions of the excited states would be extremely sensitive to the nature of the mean field. Measurement of transition probabilities, branching ratios, life time and static moments (electric and magnetic) can provide indirect information about the nature of these wave functions.

The main methods of population of excited states of nuclei are:

#### *a. Radioactive Decay*

Limited to low spin ( $< 8\hbar$ ) and low excitation energy

#### *b. Coulomb Excitation*

Moderate spins (up to  $30\hbar$ ) can be populated in the actinide region. Only stable nuclei and excited states with large ground state overlap can be studied. Availability of energetic radioactive ion beams has opened up this field for nuclei away from stability line.

#### *c. Heavy Ion Induced Fusion*

Very high spins with moderate excitation energy (upto 30 MeV) can be studied in fusion reaction using  $\gamma$ -ray spectroscopy. States up to  $40\hbar$  in normal and  $60\hbar$  in superdeformed bands have already been identified. By a proper choice of target and projectile combination, nuclei far away from the valley of stability can be populated. Further developments include the production of exotic beams to further extend the range of nuclei reached by fusion reaction.

#### *d. Direct Reactions*

Reactions of the type  $(p, p')$ ,  $(p, n)$ ,  $(p, d)$ ,  $(p, t)$ ,  $(p, \alpha)$ ,  $(p, \alpha')$  can be used to study the low lying levels of nuclei near stability line. Due to limited  $J$ -transfer, only low spin levels can be studied by this method.

### *e. Deep-Inelastic Reactions*

A wide range of nuclei far away from the stability line can be studied using this technique. Due to poor selectivity, identification of the nuclei populated is a big challenge to the experimentalists.

### 1.2.3. Heavy Ion Fusion-Evaporation Reactions

The experimental approach to high-spin states has relied on only a few methods for production. These are

- Radioactive decay
- Coulomb excitation
- Heavy ion induced fusion.

Early evidence for shell model isomers came mostly from  $\beta$ -decay studies [17], and  $\alpha$ -decay provided systematic evidence for the occurrence of rotational states up to spins of 6 or  $8\hbar$  in the actinide region of nuclei [18], just at the time the rotational model was proposed. Coulomb excitation refers to the purely electromagnetic excitation of nuclear states (usually in a collision where there is insufficient energy to penetrate close enough to involve the nuclear forces). This process was essentially born with the rotational model, and immediately established the large electric-quadrupole transition probabilities implied by deformed nuclei [19]. Projectiles with high charge (heavy ions) were found to excite successively a number of rotational transitions ( $\Delta I = 2$ ) in a single collision, culminating in 1977 [20] with the excitation of a state having  $30\hbar$  in  $^{238}\text{U}$  using  $^{208}\text{Pb}$  projectiles. Coulomb excitation has the advantage of giving transition moments as well as high spins, but can reach only about half way to the highest nuclear spins, and thus eventually gave way to a third method.

When two nuclei collide at energies above the Coulomb barrier, one of the main processes can be fusion, in which all the angular momentum of the initial system is retained (see Fig. 1.5.). The amount of angular momentum depends on the projectile bombarding energy, and impact parameter, and values up to about  $25\hbar$  were brought in by  $^4\text{He}$  projectiles during the first experiments in 1963 [21]. By 1968 [22]  $^{40}\text{Ar}$  projectiles were used and they can easily bring more than  $100\hbar$  into the compound system. This method then brings in all the angular momentum the nucleus can hold; the problem is to identify what happens in those events involving the highest angular momentum. It is not so difficult to isolate events from a particular channel leading to a certain final product

nucleus but even then, above about  $20\hbar$ , one finds essentially no resolved lines because the population is spread over too many states. According to taste, some experiments have responded by following the resolved lines further up in spin (or down in intensity) or by hunting for isomers that would provide much greater sensitivity for resolved lines.

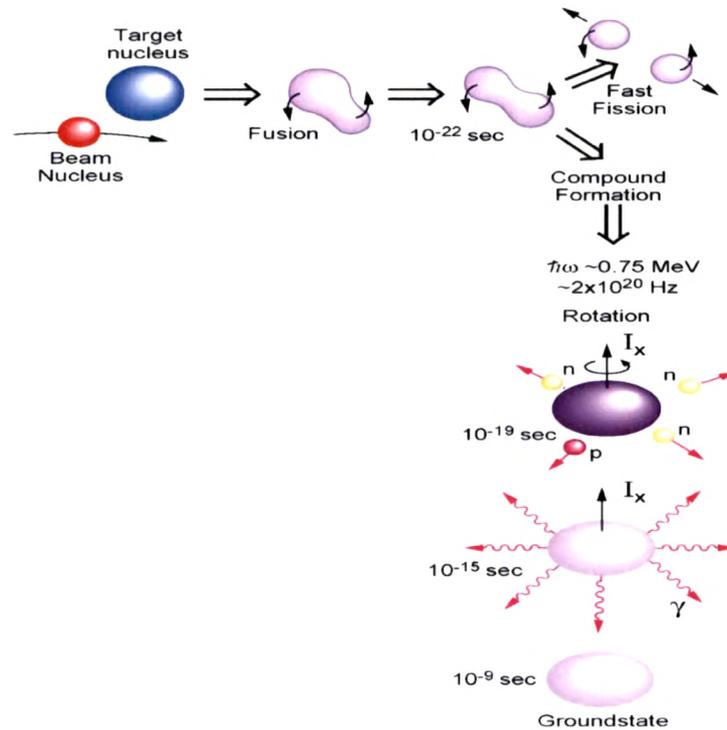


Figure 1.5: The schematic diagram of production of high angular momentum states in nuclei.

The major advantage of heavy ion induced fusion reactions is that very high angular momentum is brought up into the system. The minimum bombarding energy required to perform the reaction must be a little above the Coulomb barrier with the beam current, typically of the order of few  $nA$ . Another major advantage is that by proper choice of the projectile energy, only a few exit channels open up. The reaction kinematics in a heavy-ion induced fusion reaction ensures that the compound nucleus formed would have its spins aligned in a plane perpendicular to the beam axis and  $\gamma$ -rays resulting from the decay of compound nucleus exhibits angular distribution. The evaporating particles from the compound nucleus do not affect the angular momentum appreciably, since each of them carries away only a small amount of angular momentum ( $<2\hbar$ ), due to centrifugal

barrier. Thus the angular momentum has its magnitude almost unchanged since the stretched transitions disturb its orientation only slightly. This strong alignment obtained is a useful tool for estimating the spin-parity, moments and mixing ratios from the coincidence measurements. Thus the heavy-ion induced reactions not only populate a very high spins, making possible the complete spectroscopy studies at such high angular momentum.

#### 1.2.4. Production of High-spin States

##### 1.2.4.1. Formation of a Compound Nucleus

The method used for producing high-spin states depends on what kind of high-spin states is meant. In the light elements one would probably choose a transfer reaction with an appropriately high  $l$ -window. In the spin  $20 - 30\hbar$  region of heavier elements ( $A \geq 100$ ), Coulomb excitation would be an extremely important method.

The idea that a target and projectile nucleus fuse to form a compound system, whose subsequent decay is independent of its formation, goes back to Niels Bohr [23]. Independent decay means that the system remembers nothing of the entrance channel, except that required by conservation laws, notably here, angular momentum. No evidence contrary to this idea has been found, though we now know that "composite" systems can be formed which, for various reasons, live for a much shorter time than the compound systems ( $\sim 10^{-17} - 10^{-18}$  sec), and consequently remember more about the entrance channel. The analysis of such a complex interaction can be understood within the framework of Statistical model. It treats the nuclear reactions as a two-step process.

1. The collision of the target and the projectile leading to the formation of the compound nucleus, and
2. The decay of the compound nucleus into one of the available exit channels.

Employing the statistical model [24], one could describe effectively the formation and decay of the compound nucleus into one of the available decay channels. The effects of the angular momentum, excitation energy, shell effects and the competition between various decay modes (particle evaporation) of the compound nucleus could also be studied. There are a number of computer codes available for the prediction of the decay of the compound nucleus. CASCADE [25], PACE [26], ALICE [27] are a few examples of such evaporation codes.

#### 1.2.4.2. Decay of Compound Nucleus

The decay of the compound nucleus is described by the statistical model [28]. More details can be found in the references of Grover and Gilat [29], Thomas [30]. This model assumes that each state decays independently of its formation into one of the open channels, according to the width of the channel. The open channels in the present case are mainly fission and the evaporation of neutrons, protons, and  $\alpha$  particles. In the presence of a barrier (Coulomb or centrifugal or any other potential barrier), the population probability of that open channel is reduced by the corresponding barrier penetration probability. Thus the probability of decay to a particular open channel becomes inversely proportional to the total number of open channels. The decay process is determined by the density of nuclear states of parent and daughter nuclei, the transmission co-efficient for the evaporated particles, and the barrier penetration probability in the presence of any barrier. The probability,  $P$ , that the particle emission would result in the formation of a residual nuclei with excitation energy  $E_x$  and angular momentum  $J_x$  from a compound nucleus with initial excitation energy  $E_c$  and angular momentum  $J_c$

$$P(J_c, E_c \rightarrow J_x, E_x) \propto \rho[J_x, E_x] T_l(E), \quad (1.4)$$

where,  $\rho$  is the nuclear level density and  $T_l(E)$  are the transmission co-efficient of evaporating particles of orbital angular momentum  $l$  and energy  $E$ . An accurate description of the cross-section of various decay channels requires the knowledge of the nuclear level density at all excitation energies and angular momenta.

Characteristically different features are encountered in the decay of the compound nucleus, depending on its mass, charge and the amount of angular momentum it possesses. Neutron emission is the most dominant mode of decay at all excitation energy and angular momentum, because of the absence of the Coulomb barrier. Each step of neutron emission reduces the excitation energy equivalent to the sum of the neutron separation energy and the kinetic energy of the emitted neutron. However in light nuclei ( $A \leq 100$ ), the Coulomb barrier (which otherwise inhibits the emission of charged particles) is small. Hence proton and  $\alpha$  particles compete favorably with neutron emission. If the angular momentum of nucleus is high, the low centrifugal barrier seen by  $\alpha$  particles makes them the favored mode of decay. The increased neutron separation energies for neutron-deficient nuclei further enhance charged particle emission. As a result, for center of mass energies close to the Coulomb barrier  $p2n$  and  $2pn$  channels generally have higher yields as compared to  $3n$  channels. For heavy nuclei ( $A \sim 200$ ), characterized by high fissionity and

low fission barriers, emission of charged particles is hindered and either neutron emission or fission is the favored mode of decay. Neutron emission takes the nucleus further off the stability line while the proton emission brings it closer. The particle evaporation dominates the decay mode till the excitation energy falls below the particle separation energy. Particle decay carries away only a small amount of angular momentum, since for protons and neutrons higher  $l$  values are inhibited due to the centrifugal barrier. However,  $\alpha$  particles could carry a significant amount of angular momentum away from the compound nucleus. The compound nucleus decay is diagrammatically shown in Fig. 1.6.

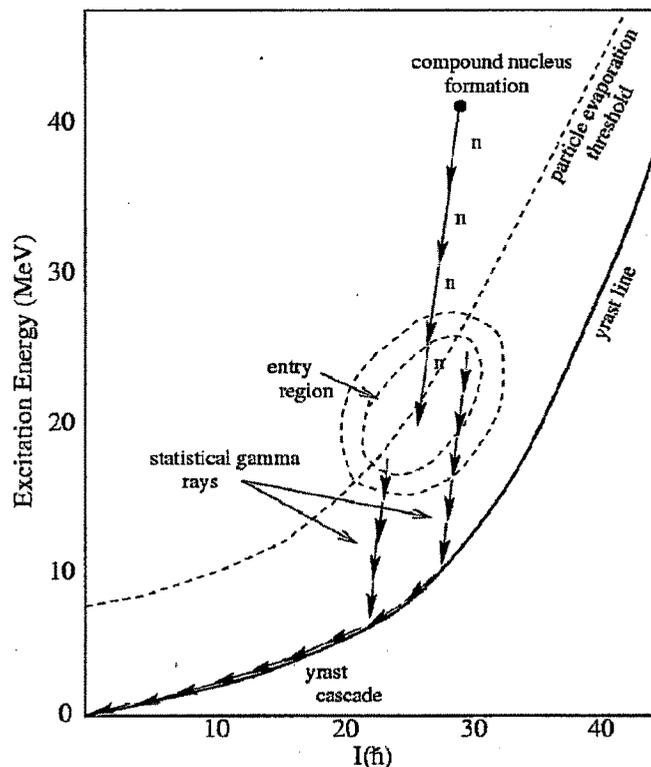


Figure 1.6: Schematic diagram showing the decay of a compound nucleus following a fusion evaporation reaction.

### 1.3. Single particle and Collective Motion

In general, nuclear excitation may exhibit two extreme types of behaviour: (i) single-particle excitations of the individual valance nucleons to different single-particle levels, and (ii) collective modes of excitation involving a coherent motion of the nucleus as a whole. Excitations of the first type imply a change of the intrinsic configuration. Those of

the second type generally mean that a particular nucleon configuration collectively vibrates and rotates. The interplay between the single-particle and collective excitation modes underlies an astounding diversity of experimental level schemes.

Quantum mechanical rotation of a perfect sphere shown in Fig. 1.7 (a) is not a meaningful concept, since no orientation can be assigned to it. However, the assumption of axially symmetric spheroidal (deformed) nuclei depicted in Fig. 1.7 (b) and (c) allows a possible nuclear rotation about the axis of perpendicular to the symmetry axis, that is,  $y$  or  $z$  axis. Hence, the description of the experimental spectra from the rapidly rotating nuclei [31] is based on the collective type of excitations, while non-collective (single-particle) mode of motion is shown by spherical or near spherical nuclei.

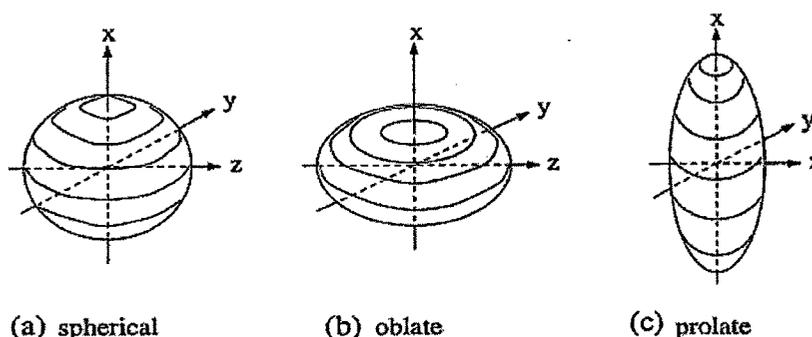


Figure 1.7: A diagrammatic representation of three types of nuclear shape (a) Spherical, (b) oblate and (c) prolate. The  $x$ -axis denotes the symmetry axis of the oblate and prolate shapes.

### 1.3.1. Single particle Motion

The coupling of individual nucleon spins is the main mechanism for generating angular momentum in spherical or weakly deformed systems. Transitions in such nuclei are non-collective. Their decay schemes consequently exhibit an irregular sequence of states connected by  $\gamma$ -ray transitions of different multiplicities. The single-particle mode of motion is mainly observed in spherical and near spherical nuclei. The angular momentum is generated by the alignment of the nucleons spins along the symmetry axis as shown in Fig. 1.8 (b). This mode leads to an irregular level scheme like the one associated with the  $^{147}\text{Gd}$  nucleus [32], for example. The angular momentum vector,  $j_i$  for the individual nucleons are summed to produce the total angular momentum vector.  $I = \sum j_i$ . Even-even nuclei always have a total angular momentum  $I = 0$ , at the ground state.

### 1.3.2. Rotational Motion

On the other hand, well deformed systems (those characterised by non-spherical mass distribution) often exhibit extremely regular sequences of states with consecutively increasing angular momentum. These are known as rotational bands. The possibility of rotational motion is a direct consequence of deformation. It involves the coherent contributions of many nucleons and is thus considered to be collective motion. Rotation takes place about an axis perpendicular to the symmetry axis. The relation between the excitation energy  $E$  and angular momentum  $I$  for a rotational band usually follows the well known  $E \sim I(I+1)$  rule. The lowest state of the band is referred to as the bandhead. It may be seen that in the Fig. 1.8 (a) the decay sequence is extremely regular and contrasts sharply with the haphazard level structure of  $^{147}\text{Gd}$ . Nuclei with a strong prolate deformation show the best examples of rotational bands. Hence the angular momentum,  $I$  of the nucleus is given by the sum of the orbital angular momentum projections on the rotation axis.

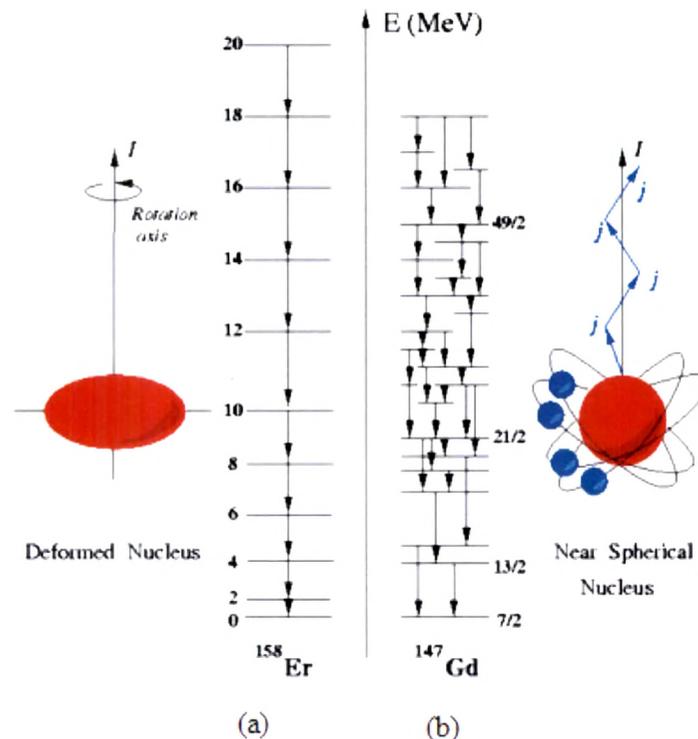


Figure 1.8: Schematic illustration of the (a) collective motion around the axis perpendicular to the symmetry axis and (b) single-particle motion, generating angular momentum,  $I$  by summing the orbital angular momentum projections onto the symmetry axis.

#### 1.4. Angular Momentum in Nuclei

The shell model best describes lighter nuclei. In heavier nuclei, a combination of effects means that valence nucleons are able to occupy more than one j-shell, especially if the shell spacing is smaller than the pairing interaction,  $\Delta$ . The development of the deformed shell model was very successful and in some way explains the observed phenomena. However, it was apparent that it did not provide a complete description of the excited states of the nucleus. Unable to find a microscopic model for some of the phenomena observed in nuclei, Bohr and Mottelson [33, 34] developed a macroscopic model of the nucleus to describe the collective excitations. The nucleus can undergo collective vibrations, and the most obvious characteristic of having deformed, non-spherical nuclear shapes, is that they can undergo rotation. These effects can also be combined to give rotational bands built upon vibrational excited shapes.

#### 1.5. The Coulomb Barrier

This is the most familiar barrier that is present because of the electrostatic repulsion between the positively charged target nucleus and the positively charged projectile. As the two partners are of comparable mass, the system is more easily described in terms of their relative motion in the center-of-mass system. The illustration of the forces that form a Coulomb barrier between the participating nuclei in a nuclear reaction is shown in Fig. 1.9.

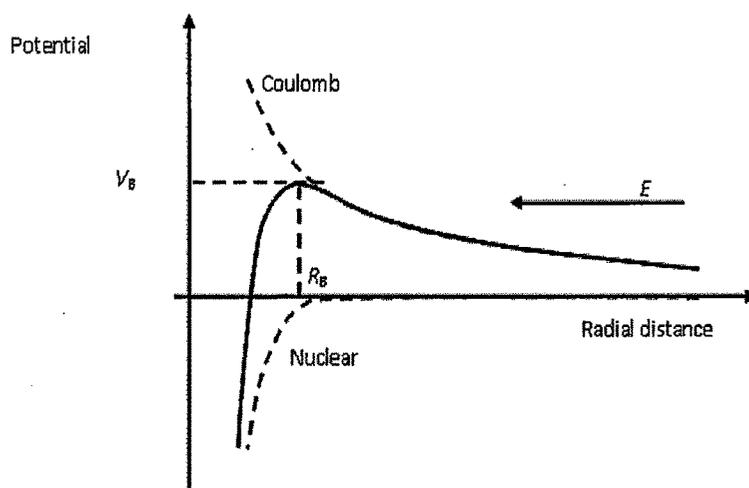


Figure 1.9: The illustration of the forces that form a Coulomb barrier between the participating nuclei in a nuclear reaction.

Assuming the standard laboratory situation of a fixed target, which is bombarded with a beam of projectile nuclei, the relation between the kinetic energy  $E_{lab}$  as measured in the laboratory system and the kinetic energy  $E_{cm}$  in the center-of-mass system is given by

$$E_{cm} = \frac{A_t}{A_t + A_p} E_{lab}, \quad (1.5)$$

where,  $A_p$  and  $A_t$  represent the mass number of the projectile and target nuclei, respectively. Electron masses and differences in binding energy per nucleon may be ignored as a good approximation. The motion of the center-of-mass is fully determined by the kinematics of the reaction and can be calculated from the bombarding energy and the nuclear masses.

### 1.6. Magic Nuclei and Shell Closures:

It is well known that atoms with 2, 10, 18, 36, 54 and 86 electrons have all their atomic shells completely filled. Such electronic structures have high binding energy and are exceptionally stable. The same kind of effect is observed with respect to nuclei that have 2, 8, 20, 28, 50, 82, 126 neutrons or protons. These are more abundant than other nuclei of similar mass numbers, suggesting that their structures are more stable and are referred to as magic numbers. Nuclei with  $N$  and  $Z$  as magic numbers are found to have zero quadrupole magnetic moments and hence are spherical, while other nuclei are distorted in shape.

The shell theory assumes that  $LS$  coupling holds only for the very lightest nuclei, in which the  $l$  values are necessarily small in their normal configurations. In this scheme, the intrinsic spin angular momenta  $S_i$  of the particles are coupled together with a total spin momentum  $S$ . The orbital angular momenta  $L_i$  are separately coupled together into a total orbital momentum  $L$ . Then  $S$  and  $L$  are coupled to form a total angular momentum  $J$  of magnitude  $\sqrt{J(J+1)}\hbar$ . After a transition region in which an intermediate coupling holds, the heavier nuclei exhibit  $jj$  coupling. In this case the  $S_i$  and  $L_i$  of each particle is first coupled to form a  $J_i$  for that particle of magnitude  $\sqrt{j(j+1)}\hbar$ . The various  $J_i$  then coupled together to form the total angular momentum  $J$ . The  $jj$  coupling scheme holds for the great majority of nuclei. The spin-orbit interaction splits each state of given  $j$  into  $2j+1$  substates, since there are  $2j+1$  allowed orientations of  $J_i$ . The number of available nuclear

states in each shell is in ascending order of energy 2, 6, 12, 8, 22, 32, 44. Hence shells are filled when there are 2, 8, 20, 28, 50, 82, and 126 neutrons or protons in a nucleus.

### 1.7. An Overview of Nuclear Structure

In spite of significant progress in establishing the structure of nuclei during the last couple of decades, we are still lacking a precise and complete knowledge of the behaviour of the nucleus. For example, it is currently impossible to predict even the exact limits of stability. In the course of recent studies, new questions have merged about the properties of the nucleus at the limits of excitation energy, angular momentum, isospin and mass. Penetration to unexplored extremes in these quantities is likely to reveal fundamentally new phenomena. The first observations along this way are, the new state of matter associated with the halo nuclei, the surprising breakdown of the established magic numbers and the existence of extremely deformed shapes in nuclei. One major reason for the study of exotic nuclei, i.e. nuclei with extreme values of the proton-to-neutron ratio  $Z/N$ , is to provide more basic data, for increasingly unstable systems, that will help to answer these open questions. One excellent example is our new understanding of shell structure based on how shell closures develop as proton and neutron numbers change.

Investigations at the limits of existence, at and even beyond the drip-lines, have revealed new and completely unforeseen structures. Pushing the  $N/Z$  ratio to extreme values has resulted in the discovery of halo nuclei and other new exotic nuclei at or near the proton and neutron drip lines. They present interesting problems in themselves and lead to a deeper comprehension of the nucleus in general. At the extremes of excitation energy and angular momentum nuclear structure studies are probing nuclear shapes and their evolution, the influence of the thermal environment on low modes of excitation and giant modes of excitation. The most conspicuous findings have concerned superdeformed bands and the spectroscopy of strongly deformed shapes. Equally surprising was the observation of superdeformed rotational bands with almost identical level spacings in neighbouring nuclei. Current theoretical models are stretched to their limits to encompass the wealth of observed new phenomena. One of the strengths of present nuclear theories is the ability to describe simultaneously single particle and collective modes of excitation. The coexistence of these modes at the same excitation energy is one of the most striking and original features of nuclear dynamics. In the new regions of the nuclear chart, mean

field theories, large scale shell model descriptions and cluster models are the necessary tools to achieve this goal.

The rapid growth in computational power has allowed us to calculate the complicated wave functions which are needed for a full shell model description of the ground state and low-lying collective states of medium mass nuclei. Of vital importance has been the continuing innovation in instrumentation, with advances in highly efficient ion sources and accelerators, recoil-separators, traps and storage rings. The development of ultra-sensitive detection of nuclear radiation with high resolving power, fast data acquisition and modern hardware and software for computing, have opened up new frontiers in the nuclear structure research. In studies of high spin excitations, powerful detector arrays, based on Compton suppressed Ge detectors have been in full operation.

### 1.8. Motivation of the Present Work

Nuclei close to the shell closures, with a few valence particles are always interesting, for they furnish data useful in constructing empirical shell model Hamilton consisting of single-particle energies (SPEs) of the valence orbitals and the residual nucleon-nucleon interaction matrix elements. In view of this, the present work was motivated to investigate the single particle and collective level structures of nuclei in the vicinity of proton shell closures. In particular we have chosen to investigate the high-spin states in:

### 1.9. Difficult to Access Odd-Odd Nuclei near Proton Shell Closures ( $Z \sim 20, 28$ )

#### 1.9.1. Spectroscopy of $^{36}\text{Cl}$

The level structure of the odd-odd  $^{36}\text{Cl}$  is expected to be interesting due to the proximity of both the proton and neutron numbers to the  $Z, N \sim 20$  shell closure. Information on the level structure of this nucleus is available from single-neutron stripping and pickup reactions, and hence is limited to moderate spins and excitation energy. The work has since been reported in more detail by Nolan *et al.*, [35], Del Vecchio *et al.*, [36], Nann *et al.*, [37]. The  $^{25}\text{Mg}(^{16}\text{O}, \alpha p \gamma) ^{36}\text{Cl}$  reaction was used by Keinonen *et al.*, [38], while Warburton *et al.*, [39] used the  $^{27}\text{Al}(^{14}\text{N}, \alpha p \gamma) ^{36}\text{Cl}$  and  $^{24}\text{Mg}(^{18}\text{O}, \alpha p n \gamma) ^{36}\text{Cl}$  reactions. It would be of interest to explore the level scheme to higher spin regimes, where one could expect configurations originating from nucleon excitations from the  $(2s, 1d)$  shell into the  $(1f, 1p)$  shell. Further the availability of a reasonable number of valence nucleons outside

the core could result in the occurrence of deformed structure at high spins in this nucleus. In present work, the high spin states in  $^{36}\text{Cl}$  were populated using the  $^{20}\text{Ne} + ^{27}\text{Al}$  reaction.

### 1.9.2. Spectroscopy of $^{54}\text{Mn}$

The studies of odd-odd nuclei offer a scope for investigating the underlying proton-neutron residual interaction. Such nuclei exhibit highly complex level structure due to a large number of possible couplings of the odd proton and neutron to the even-even core. For nuclei above mass  $A = 40$  the  $N = Z$  line drifts more and more away from the line of stability with increasing mass number. A rather small Coulomb barrier gives rise to an interesting aspect of the heavier  $N \sim Z$  nuclei, namely the proton, alpha, or even cluster emission that play a role in the decay of their excited states. The excitation spectra in the low-energy region for these nuclei show irregular and complex patterns, typically for near spherical nuclei and are dominated by single- and multi-particle excitations. Spectroscopic information on these nuclei provides important avenues to the empirical single particle energies and the residual N-N interactions needed for understanding the nuclear structure in shell model framework.

A variety of physics of the odd-odd nuclei has been studied in the mass  $A \sim 50$  region [40 - 43]. Smooth band termination was observed by BaoGuo *et al.* [44], in the odd-odd nuclei  $^{46}\text{V}$  and  $^{50}\text{Mn}$ . Both these nuclei are normally deformed with no sign of shape coexistence within the same configuration. But there is no such existing data on the next odd-odd nuclei  $^{52}\text{Mn}$ ,  $^{54}\text{Mn}$ , which shows band termination. Different investigations have been carried out by Poletti *et al.* [45], Nathan *et al.* [46], Radford and Poletti [47], Toulemonde *et al.* [48] to study the level structure of  $^{54}\text{Mn}$  up to an excitation energy of  $E_x \sim 4$  MeV and spin-parity of  $J^\pi \sim 8^+$ , using different techniques such as coincidence measurements, Doppler Shift Attenuation Method (DSAM), Recoil Distance Method (RDM). They have used alpha beams and light heavy ion beams viz.,  $^7\text{Li}$ ,  $^{11}\text{B}$  to study the level structure of  $^{54}\text{Mn}$ . Parker *et al.* [49] have used the reaction  $^{20}\text{Ne} + ^{51}\text{V}$  with a beam energy of  $\sim 6$  MeV/A to study the complete fusion residue cross-section studies in mass  $A \sim 55$  region. They could study the residue yields fairly well for the complete fusion products, but could not explain the production of the residue  $^{54}\text{Mn}$ . The authors suggested that apart from the complete fusion, various other processes might contribute significantly to the production of  $^{54}\text{Mn}$ . The mechanism of incomplete fusion (ICF) [50] has been the subject of considerable interest to populate such nuclei at



together with the low-K neutrons form highly irregular bands built of M1 and E2 transitions [59, 60]. In  $^{190}\text{Hg}$  however, a competition between these types of bands is observed [61]. None of the heavier Tl isotopes is known up to the spins where the proton pair is excited. Thus, studying the level scheme of  $^{195}\text{Tl}$  will provide insight on the proton excitations in these nuclei and the competition between the shears bands and the irregular  $\pi h_{11/2}^2$  bands.

In order to explore these mass regions of interest, we have successfully exploited different reaction mechanisms. The first experiments to study the structure of nuclei  $Z \sim 20$  and 28 were performed with heavy ions using the INGA (Indian national Gamma Array) facility then stationed at VECC (Variable Energy Cyclotron Centre), Kolkata, India. The reactions employed were  $^{20}\text{Ne} + ^{27}\text{Al}$  and  $^{20}\text{Ne} + ^{51}\text{V}$  both at 145 MeV of projectile energy. And to explore the  $Z \sim 82$  mass region we have successfully employed AFRODITE gamma detector array, iThemba LABS, Cape Town, South Africa. Here we have used the Oxygen beam onto the Tantalum foil ( $^{18}\text{O} + ^{181}\text{Ta}$ ) at lab energy of 83 MeV.

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