CHAPTER-I

1.1 PREHISTORY OF NUCLEAR PHYSICS

Nuclear physics is a stimulating subject, in an attempt to explain the structure of atom, J. J. Thomson suggested that the atom consisted of an equal number of positive and negative charges (proton and electron) distributed uniformly within its spherical volume. The radius of the atom was estimated to be the order of 10^{-10} meters. Since the famous α- ray scattering developed by Rutherford (1911), established that the mass of an atom is concentrated within a small, positive charge region at the centre of the atom. This central core is surrounded by electron cloud, is called nucleus. Since Rutherford's times many scattering experiments, using highly energetic electron and neutrons as the scattering particles, have been performed to determine the size of nucleus. Later, Chadwick (1932) discovered the neutron as the constituent of nucleus. Heisenberg (1932) introduced the concept of isospin, viz. that proton and neutron merely two different states of the same elementary particle known as nucleon. From the phenomena of nuclear fission of heavy nuclei, Neils Bohr developed the liquid drop model based on strong interaction of the nucleons. However, Mayer (1949, 1950) proposed the nuclear shell model based on the average field produced by all the nucleons moving independently in the potential well. The regular rotation like spectra in medium mass nuclei led Bohr and Mottelson (1953) to develop the collective model, a combination of the liquid drop model and shell model.

It is well known that the nuclear model is applicable in explaining the different nuclear properties such as prediction of energies of g-band, β-band, γ-band and other higher multi phonon bands or B(E2) values and B(E2) ratios for inter and intra band transitions of nuclei for light and medium mass region with varying degrees of success. In this chapter we give the basic definition, useful concept and facts relating to the consequent chapters. This chapter also sketches the brief summary of theoretical models which have been used in the present thesis work for understanding of experimental data and the collective nuclear structure.

In this chapter we give the brief summary of the different types of models.

1.1.1 Angular Momentum of Nuclei

The angular momentum **L** of a particle about a given origin is defined as:

$$\mathbf{L} = \mathbf{r} \times \mathbf{p} \tag{1.1}$$

where, **r** is the position vector of the particle relative to the origin, **p** is the linear momentum of the particle and × denotes the cross product. The derived SI units of angular momentum is Newton meter second (N·m·s or kg·m^2/s) or Joule- second (J·s). Because of the cross product, **L** is a pseudo vector perpendicular to both the radial vector **r** and the momentum vector **p.** For an object with a fixed mass that is rotating about a fixed symmetry axis, the angular momentum is expressed as the product of the moment of inertia (I) of the object and its angular velocity (**ω**) vector:

$$\mathbf{L} = I\boldsymbol{\omega} \ . \tag{1.2}$$

The angular momentum of a particle or rigid body in rectilinear motion (pure translation) is a vector with constant magnitude and direction. If the path of the particle or centre of mass of the rigid body passes through the given origin, its angular momentum is zero. Angular momentum is also known as moment of momentum.

1.1.2 Electric Quadrupole Moment of Nuclei

The nuclear electric quadrupole moment is a parameter which describes the effective shape of the ellipsoid of nuclear charge distribution. A non-zero quadrupole moment Q indicates that the charge distribution is not spherically symmetric. By convention, the value of Q is taken to be positive if the ellipsoid is prolate and negative if it is oblate.

1.1.3 Nuclear Forces

Every nucleus consists of protons and neutrons (known as nucleons). The nuclear forces acting between these nucleons, called nuclear force. These forces have been discovered by James Chadwick studied in terms of models, and since models do not involve the detailed behavior of these forces, we have learned only about certain of their general features. To a large extent, this force can be understood in terms of exchange of virtual light meson, such as the pions. Sometimes the nuclear force is called the residual strong force. Further, characteristics of the nuclear force are the following.

(i) The nuclear force is short range and central, with small non-central part.

(ii) The nuclear force is repulsive at very short range to prevent the collapse of the nucleus.

(iii) The constants density and binding energy per nucleon (B/A) indicates the saturation property of the nuclear force.

(iv) As nucleons are Fermi-Dirac particles (spin) the nuclear force exhibits the saturation property of the nuclear force.

(v) The nuclear force is charge independent i.e. neutron-neutron (n-n), proton-proton (p-p), neutron-proton (n-p) interactions are equal.

(vi) The main knowledge about the nucleon interaction came from the p-p, n-p scattering experiments and study of deuteron.

1.1.4 Magic Number and Stability of Nucleus

It has been observed that nuclei have protons and neutrons. If numbers of any of these nucleons Z or N is equal to 2, 8, 20, 28, 50, 82 and 126 then the nucleus becomes more stable. These numbers are called *magic numbers*. If both N and Z are magic numbers, then nucleus becomes very stable. The existence of magic number is explained using shell model and it also describes spin and parities of low lying state of closed major shell nuclei. At this number of nucleon a shell becomes complete.

1.2 LIQUID DROP MODEL

The liquid drop model in nuclear physics treats the nucleus as a drop of incompressible nuclear fluid. It was first proposed by George Gamow and then developed by Niels Bohr and John Archibald Wheeler. The fluid is made of nucleons (protons and neutrons), which are held together by the strong nuclear force. This is a basic model that does not explain all the properties of the nucleus, but does explain the spherical shape of most nuclei. It also helps to predict the binding energy of the nucleus.

Mathematical analysis of the theory delivers an equation which attempts to predict the binding energy of a nucleus in terms of the numbers of protons and neutrons it contains. This equation has five terms on its right hand side. These correspond to the cohesive binding of all the nucleons by the strong nuclear force, the electrostatic mutual repulsion of the protons, a surface energy term, an asymmetry term (derivable from the protons and neutrons occupying independent quantum momentum states) and a pairing term (partly derivable from the protons and neutrons occupying independent quantum spin states).

If we consider the sum of the following five types of energies, then the picture of a nucleus as a drop of incompressible liquid roughly accounts for the observed variation of binding energy of the nucleus.

1.3 NUCLEAR SHELL MODEL

In nuclear physics, the nuclear shell model is a model of the atomic nucleus which uses the Pauli exclusion principle to describe the structure of the nucleus in terms of energy levels. The shell model is partly analogous to the atomic shell model which describes the arrangement of electrons in an atom, in that a filled shell results in greater stability. When adding nucleons (protons or neutrons) to a nucleus, there are certain points where the binding energy of the next nucleon is significantly less than the last one. This observation, that there are certain magic numbers of nucleons: 2, 8, 20, 28, 50, 82, 126 which are more tightly bound than the next higher number, is the origin of the shell model.

1.3.1 Successes and the Limitations of the Shell model

Shell model explains correct magic number, spin, parity, binding energy of nuclei, cross section of neutron captured by nuclei, magnetic dipole moment with some deviation from experimental observation and transition probabilities of emission of gamma rays from the nuclei.

Whereas, it gives zero quadrupole moment of the nuclei and does not give information about nuclei having more valence nucleons. This model is best for lighter nuclei.

1.4 BOHR-MOTTELSON COLLECTIVE MODEL

Unified collective model of nucleus was proposed by Bohr and Mottelson (1953). Collective model is the combination of liquid drop model. It views the nucleus as vibrating –rotating core capable of being deformed to various shapes i.e. prolate, oblate or tri-axial. This is called the geometric view of the collective motion of the nucleus. The law energy levels of the nucleus are grouped in three collective bands, called $K^{\pi}=0_1^+$ g- band; $K^{\pi}=0_2^+$ β- band; $K^{\pi}=2_1^+$ γ- band and higher energy levels are called multi-phonon bands.

The Bohr-Mottelson (1975) series expression for level energies in a band is given as:

$$E_I=AI(I+1)+B\{I(I+1)\}^2+C\{I(I+1)\}^3+..... \quad (1.3)$$

In the shell model, core is made of paired nucleons and the core may be spherically symmetric or may be axially deformed. The non spherical potential arises due the valence nucleons which polarise the nuclear core. Thus the single particle energies are calculated in a non spherical potential. In this model the nucleus consists of an even-even core plus one or more nucleons moving in the shell model orbits. The coupling of core and nucleons may be weak (or strong) which corresponds to the vibrational, rotational model.

1.4.1 Successes and the Limitations of the Collective model

In the Bohr-Mottelson model the even Z and even N nucleus has vibration and rotational motion. The vibrational model predicts the following properties:

(i) The vibrational nuclei have low lying collective excited states.

(ii) The E2 transition from two phonon triplets to one phonon 2_1^+ level is strong.

(iii) The cross over E2 transition from second 2_1^+ state to the ground state should vanish.

(iv) The Quadrupole moment of the first 2_1^+ excited states is zero.

The rotational model (RM) can explain the following properties:

(i) The energy spectrum of rotational nuclei has the ground state rotational band, β band and γ-vibration band.

(ii) The transition for ($0^+ \rightarrow 2_+$) has the large absolute B(E2) value and Quadrupole moment.

(iii) The deformed nuclei have the magnetic moment with sign and finite magnitude.

(iv) The nuclear deformation is given by the expression:

$$\beta = B(E2; 0_1^+ \dashrightarrow 2_1^+)^{\frac{1}{2}} \times \frac{4\pi}{3Z_e R_0^2} \qquad (1.4)$$

(v) The K selection rule for electromagnetic transition is $\Delta K = |K_f - K_i| \leq \lambda$, where K_i and K_f are the values of K for initial and final bands for a particular transition, and λ is mode of transition.

The limiting collective model approach could not explain the observed properties of those nuclei which posses both the rotational and vibrational model feature. In the limiting model the rotational-vibration interaction was not taken into account.

1.5 ROTATIONAL-VIBRATIONAL MODEL

The complete rotational –vibrational interaction model (RVM) was developed by Fasessler et al. (1965), which allow the diagonalization of the Bohr-Mottelson collective Hamiltonian. In this model the nucleus is assumed to be axially symmetric deformed i.e. $\beta_0>0$ and $\gamma_0=0$. The RVM succeeds in the reproduction of the low lying energy spectra of the g-, β- and γ-bands and the B(E2) ratios for transition from γ- and β-bands.

1.6 ASYMMETRICAL ROTOR MODEL

Davydov and Filippov (1958) proposed asymmetric rotor model (ARM) to investigate the energy levels corresponding to rotation of nucleus which does not change its internal state. According to which nucleus is triaxially deformed with $\gamma_0 \neq 0$ and the ground band, β-band and γ-bands are due to rotation of triaxial ellipsoid

nucleus about different axis. One can derive the value of angle of triaxiality or asymmetry parameter γ_0 from ratio R_γ as given below:

$$\gamma_0 = \frac{1}{3}\sin^{-1}\{\frac{9}{8}[1-\left(\frac{R_\gamma - 1}{R\gamma + 1}\right)^2\}^{1/2}, \text{ where } R_\gamma = \frac{E_{22}}{E_{21}}. \quad (1.5)$$

1.7 DYNAMIC PAIRING PLUS QUADRUPOLE MODEL

The dynamic pairing-plus-quadrupole (DPPQ) model was proposed by Kumar and Baranger (1967, 1968). They predicted successfully the prolate to oblate shape transition in Os - Pt region. The DPPQ model can treat spherical, deformed and transition nuclei within a single frame work. Kumar and Baranger also developed the dynamic deformation model (DDM), in which there was no inert core assumed. In DPPQ model and DDM, instead of assuming a fixed shape (axially symmetric deformed or axially deformed) the nucleus is allowed to take its own shape in the (β, γ) plane. The Bohr collective Hamiltonian is given by

$$H_C = V(\beta, \gamma) + T_{rot} + T_{vib} \quad \text{with} \quad (1.6)$$

$$T_{rot} = \frac{1}{2}\sum_{k=1}^{3}\theta_k(\beta,\gamma)\,\omega_k^2 \quad \text{and}$$

$$T_{vib} = \frac{1}{2}\{B_{\beta\beta}(\beta,\gamma)\dot{\beta}^2 + 2B_{\beta\gamma}(\beta,\gamma)\dot{\beta}\beta\dot{\gamma} + B_{\gamma\gamma}(\beta,\gamma)\beta^2\dot{\gamma}^2\}$$

where θ_k (k=1, 2, 3) are the nuclear moment of inertia, ω_k is the angular velocities, $B_{\beta\beta}$, $B_{\beta\gamma}$, $B_{\gamma\gamma}$ are the three mass parameters for β-vibrations, β-γ coupled motions, γ-vibrations. All the coefficients of H_c are determined from the solution of H_{PPQ}.

1.8 INTERACTING BOSON MODEL

The interacting boson model (IBM) is a model in nuclear physics in which nucleons pair up, basically acting as a single particle with boson properties, with integral spin of 0, 2 or 4.

The IBM-I treats both types of nucleons the same and considers only pairs of nucleons together to total angular momentum 0 and 2, called respectively, s- and d-bosons. The IBM-II treats protons and neutrons separately. The IBM is suitable for describing intermediate and heavy atomic nuclei. Adjusting a small number of parameters, it reproduces the majority of the low-lying states of such nuclei. This model of the atomic nucleus has to be able to describe nuclear properties such as spins and energies of the lowest levels, decay probabilities for the emission of gamma quantas, probabilities (spectroscopic factors) of transfer reactions, multiple moments and so into the world. Outlined from which the IBM comes. This theoretical result is not far from the real situation of even-even nuclei, from which it is known that their total spin mainly is even. These and other arguments lead to the basic statement of the IBM which Postulates that the nucleon pairs are represented by bosons with angular momentum L = 0 or 2. The multitude of shells which appears in the shell model is reduced to the simple s-shell (L= 0) and the d-shell (L = 2) which is composed vectorially by d-bosons analogously to the shell model technique. The IBM builds on a closed shell i.e. the number of bosons depends on the number of active nucleon (or hole) pairs outside a closed shell. Each type of bosons, the s- and the d-boson, has its own binding energy with regard to the closed shell. Analogously to the standard shell model, the interacting potential of the bosons acts only in pairs.

Moreover, the number of bosons is unlimited and is not a good quantum number in compare to the situation in the IBM. The simplest versions of the IBM describe the even-even nucleus as an inert core combined with bosons which represent pairs of identical nucleons. The analogy between nucleon pairs and bosons does not go so far that in the IBM the wave functions of the corresponding nucleons would appear. However, in the interacting boson-fermions model which deals with odd numbers of identical nucleons, bosons are coupled to nucleons.

The models IBM1 and IBM2 are restricted to nuclei with even numbers of protons and neutrons. In order to fix the number of bosons one takes into account that both types of nucleons constitute closed shells with particle numbers: 2, 8, 50, 82 and 126 (magic numbers). Three-boson interactions are excluded in analogy with the assumptions of the standard shell model. In contrast to the collective model, in the IBM one does not obtain a semi classical, vivid picture of the nucleus but one describes the algebraic structure of the Hamiltonian operator and of the states, for which reason it is named an algebraic model.

1.9 SUBJECT OF STUDY IN THIS THESIS

1.9.1 Chapter 1

The current work is based on the study of nuclear structure for A=150-200 for medium mass region. The study is carried out by in-between this A=150-200 region in four quadrants. We studied all the models, viz, the geometrical, empirical and group theoretical models. The predictions of these models have been compared with available experimental data.

1.9.2 Chapter 2

In Chapter II, the theory of nuclear models such as liquid drop model, nuclear shell model, collective model, dynamic- pairing –plus quadrupole model, interacting boson model etc. are discussed.

1.9.3 Chapter 3

In Chapter III, the values of asymmetry parameter (γ_0) of Davydov and Filippov model (1958) are calculated using the experimental energies of $E2_2^+$ and $E2_1^+$ states. Its variation with N, Z, NpNn, N_B is studied qudrant wise.

1.9.4 Chapter 4

In Chapter IV, the predictions of asymmetric rotor model of Davydov and Filippov (1958) for B(E2;4g→2g)/B(E2;2g→0g) branching ratio are compared with the recent experimental data in medium mass region.

1.9.5 Chapter 5

In Chapter V, the interacting boson model-1 of Arima and Iachello (1976) is applied to study the nuclear structure of $^{152, 154}$Sm isotopes. The predictions of IBM are compared with the experimental data and the data of other nuclear models.