Chapter 1

Introduction

1.1 Radioactivity

Nature is enriched with matter and its constituents. Matter is composed of molecules. The molecules are made up of smallest particles called atom and this tiny entity consists of nucleus as its core. The protons and neutrons bind together with the strong attractive force resulting in the formation of the nucleus. Nuclei with particular number of protons and neutrons are stable and they are called magic nuclei, they tend to lie in the ground state until it gets disturbed by an external force. The nucleus with excess of protons or neutrons are unstable and they reach stability by the emission of radiation either in the form of electromagnetic waves or particles. This process of spontaneous transformation in the nucleus are called radioactive decay or radioactivity or nuclear decay. The nuclear decay studies of the unstable nucleus provide important information about the nuclear structure [1].

In 1896, the French Scientist, Henri Becquerel discovered the phenomenon of radioactivity, from Uranium salts. He did the experiment by placing a layer of the above salt on a black paper enwrapped with photographic plate and kept it under sunlight for several hours. After sometime, he had observed a silhouette of the material and confirmed that new radiation generated a ray similar to X-rays. This confirmed the emission of new type of radiation, and is capable of penetrating black paper without the influence of external factor [2]. Following this, Curies have discovered thorium salts and confirmed it as radioactive. Two radioactive elements such as radium and polonium were discovered by Pierre Curie and Marie Curie [3]. Also they have concluded that radiation emitted by the radioactive substance were not affected by any external factors [4].

Rutherford [5] has observed two types of radiation emitted by Uranium salts. The radiation were named as alpha and beta particles based on its penetrating depth and ionization power. Another type of radiation called gamma rays which has more ionization power and penetrating depth was discovered and named by Paul Villard [6]. Fig.1.1 represents the nuclear chart. Proton number (Z) is represented in x-axis and neutron number (N) is represented in y-axis. Stable nuclei are represented by red colour dots. The nuclei lying at a particular point with null separation energy is the boundary limit along the proton and neutron axis and is called proton and neutron dripline respectively. The nuclei lying in this region are unstable and they reach ground level by emitting radiation either in the form of electromagnetic waves or particles like two-proton ($2p$), one-proton ($1p$), neutron, etc.

1.2 Basic decay modes

Generally, alpha, beta and gamma decay are commonly called as basic decay modes and it is first type of decay modes. They are categorized based on their ionization power and penetration depth.

Alpha decay: Alpha particle is made up of helium nucleus which is composed of two protons and two neutrons. Geiger and Nutall [7] have proposed a systematics, to study alpha decay and its energy. According to them, the nuclei with shorter half-lives emit more energetic alpha particles and with longer half-lives emit low energy alpha particles. The height of the barrier for alpha decay is higher than the kinetic energy of the emitted alpha particle. Hence, it is difficult for the alpha particle to penetrates the potential barrier of the parent nucleus. This was explained

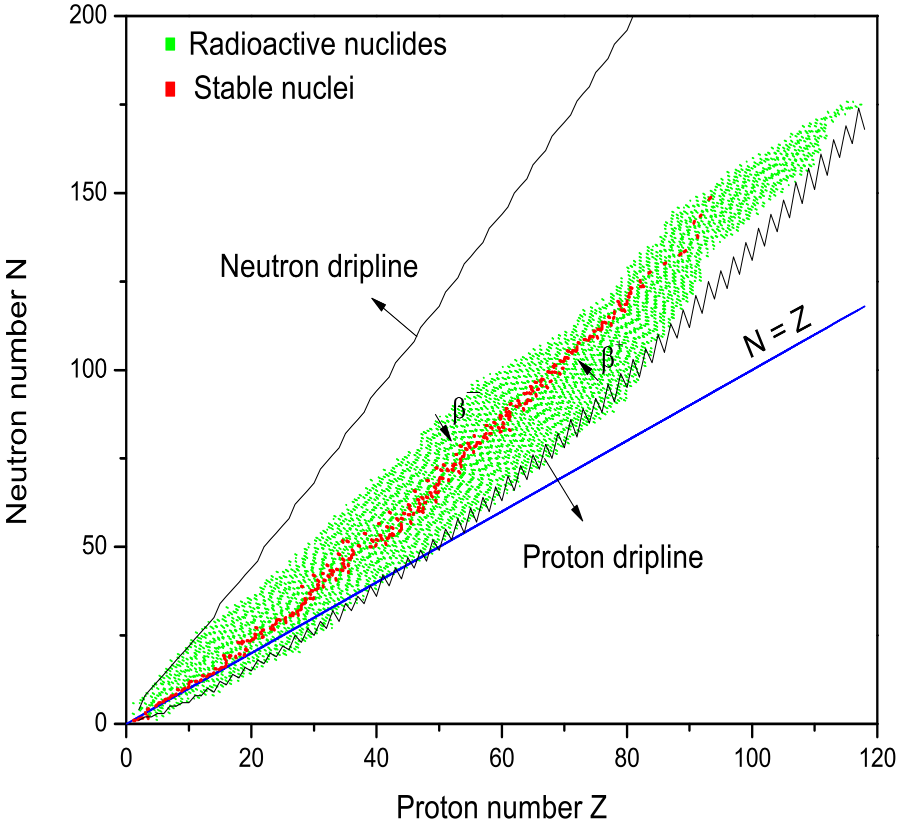

Figure 1.1: The nuclear chart represents the stable and radioactive nuclear species

by George Gamow [8] in 1928. He has developed quantum tunnelling theory based on quantum mechanics, in which the alpha particles get preformed inside the parent nucleus and it found to possess high binding energy. The alpha particle inside the barrier has made a number of hits inside the barrier wall and then tunnel or penetrate through the potential barrier. The penetrability through the barrier is solved by using Wentzel-Kramer-Brillouin (WKB) approximation. Alpha decay probably occurs in heavy and artificially synthesized superheavy elements when the Q_α-value is positive [9]. The spin and parity of the nuclear energy levels of the nuclei lying in heavy and superheavy mass region are obtained from the spectroscopic studies using alpha decay.

Beta decay: Basically, the beta decay processes are classified into three types, they are negative beta decay (β^-), positive beta decay (β^-) and orbital electron capture (ε). One of the earliest known radioactive decay processes is the nucleus emitting negative electrons. Alvarez [10] has detected the reverse process of capturing electron by the nucleus from its atomic orbits, by detecting the X-rays emitted while filling the vacancy left out by the captured electron. The positive electron emission called as positron emission, was discovered by Joliot-Curies [11] from the radioactive decay, after the discovery of the same from cosmic rays. Generally, beta particle is emitted in the basic conversion process such as proton to neutron, in the proton-rich nuclei which are lying below the stability line and from neutron to proton, in the neutron-rich nuclei which are lying above the stability line as shown in Fig. 1.1. In β-decay process, only the atomic number is either increased or decreased by one, where the mass number remains same. Neutron-rich nuclei, emit β^- or electron along with anti-neutrino, while the proton-rich nuclei emit β^+ or positron along with neutrino [12].

Gamma decay: Gamma decay was discovered in 1900, while examining the radiation emanating from the radium nucleus. The radiation is first allowed to pass through the narrow-shielded container to fall on the photographic plate via thin layer of lead. It was noticed that, among three type of radiation, alpha rays were stopped while penetrating lead and second ray got deflected by magnetic field named beta-rays and the third type was gamma rays and it was noted to have more penetrating power. The parent nucleus splits into the daughter nucleus and is left in an excited state, by the emission of alpha or beta particles or fragments. With a release of gamma rays, the nucleus in the intermediate state make transition to the ground state. Gamma rays have high penetrating power compared to other type of radiations since they are not deflected by electric or magnetic field [13].

Nuclear fission: Nuclear fission is the third type of decay mode. Since 1895, basic decays such as alpha and beta decay were studied. There was a rapid growth in the field of nuclear physics followed by the discovery of neutrons by Chadwick in 1932 [14]. This discovery brought an idea to study the behaviour of various elements while exposing to neutron beam. Using this technique, Enrico Fermi and his colleagues [15] had studied an induced radioactivity by observing the emission of β^- particles from the exposed elements, followed by its neutron capture. Further this technique is used to produce transuranium elements with atomic number greater than 92. Irradiation of uranium with neutrons, lead to β^- emission initially and the efforts to separate these elements have produced quite confusing results. The radioactivity process have given results comparatively similar to barium and it led O. Hahn and F. Strassmann [16] to discover the phenomena of nuclear fission while bombarding uranium with neutrons and observed barium atoms as the end products from the reaction. Further, many intermediate mass nuclei have been observed as the product of the reaction and found that large amount of energy of the order of 200 MeV has been released. In 1939, Lise Meitner and Frisch [17] have coined this process as fission by borrowing the word from biologists, as it is similar to cell division.

Neils Bohr and his co-author [18] have analyzed, this reaction breaks up the nucleus into two fragments and explained this process as the competition between the Coulomb forces and nuclear forces. Since it was a heavier element, the Coulombic repulsion plays a major role in its decay. Fission takes place as spontaneous process like natural decay. The nuclei lying beyond thorium undergoes fission spontaneously if a sufficient excitation energy is provided. An enormous amount of energy has been released from the neutron-induced radioactivity, since the neutron itself is enough to induce the new fission process and occurs like a chain reaction. With the advancement in the experimental techniques, this chain reaction can take place slowly or controlled inside the nuclear reactor. This process serves as a world-wide application for the generation of electricity [19].

1.3 Exotic decay modes

Besides the commonly occurring basic decay modes like alpha, beta and gamma emission, there are other numerous form of decays discovered, such as one-proton emission, two-proton emission, neutron emission and cluster emission [20]. The clusters are smaller than the smallest fission fragments but greater than alpha particle. These emissions are generally called as exotic decay modes.

One-proton radioactivity: One-proton ($1p$) radioactivity is an exotic phenomenon, in which the neutron-deficient proton-rich nuclei lying beyond the proton dripline are observed to undergo this process. One-proton radioactivity was experimentally observed in the excited state of ^{53m}Co by Jackson and his co-workers in 1970 [21] and it was confirmed by Cerny and his collaborators [22] in the same year. For the unstable nuclei which are lying away from the stability line, the binding energy of proton decreases with increase in neutron number. The odd-Z nuclei are prone to 1p emission. The nuclei lying in the mass region from A = 100 to 185 with the atomic number ranging from Z = 53 to 83, having decay energy greater than zero (i.e., $Q_{1p} > 0$), emits protons. The study clearly explains the microscopic quantities such as spectroscopic factor and structural information of the proton emitting nucleus. The proton emitting nuclei which are having lower half-lives are used for the cancer treatment in medical field. In nuclei with $Z \leq 50$, one-proton penetrate easily because of their small potential barrier height. For the nuclei with higher potential barrier, it is quite difficult. The energy and angular momentum carried by the parent nucleus are the most important factors of proton emission.

Two-proton radioactivity: Two-proton radioactivity ($2p$) was first theoretically established by Zeldovich [23] in 1960 and later it was confirmed by V. I. Goldansky [24] in the same year. It usually occurs in the nuclei lying beyond the proton dripline in which their outer protons are unable to bind themselves with one core. The nuclei with even-Z are more prone to $2p$ radioactivity. The inner structure of the nucleus and the angular momentum selection rule strongly restricts the occurrence of $1p$ emission and the strong nuclear force and electromagnetic interaction compete with one another, lead to the occurrence of $2p$ decay. Experimentally, the $2p$ detection was started in 1970s for the case of light nuclei such as ^{6}Be and ^{12}O and due to their shorter life-time, the nuclear structure has not been be understood well. For the first time, the $2p$ decay was directly observed in the ground state nucleus ^{45}Fe with longer life-time [25].

This type of radioactive decay process occurs through three different ways such as diproton emission, sequential emission and simultaneous emission. The diproton emission is the process in which the two-protons are correlated in the quasi-bound state and it exist for a while before getting separated after tunnelling the barrier. The three-body decay process occurs through the large-angle opening by emitting two-protons simultaneously from the core and the valence nucleons are positioned easily in their coordinate space and it provides the information about the nucleon wave function and its interactions. Whereas, in sequential decay, the parent nucleus emits $1p$ by reaching its immediate neighbourhood and further emit one-proton to reach its stable state and it can be treated as a two-step $1p$ emission. From these three decay mechanisms, the basic information of the nucleus like, its structure and properties can be studied. The studies of $2p$ radioactivity are helpful in the analysis of $2p$ radiative capture in nuclear astrophysics [25].

Cluster radioactivity: The exotic decay where particles heavier than alpha particle and lighter than the lightest fission fragments are emitted. This is called cluster decay. The cluster radioactivity was first theoretically predicted by A. Sandulescu *et al* in 1980 [26], using quantum mechanical fragmentation theory (QMFT). It was first experimentally observed with the detection of ^{14}C emission from ^{223}Ra with an energy of about 30 MeV with the use of solid-state counter telescope, by Rose and Jones [27] in 1984. Thus far, clusters such as ^{14}C, ^{20}O, ^{23}F, ^{22}Ne, ^{24}Ne, ^{26}Ne, ^{28}Mg, ^{30}Mg, ^{32}Si and ^{34}Si have been identified using various detection techniques [28,29]. The cluster decay occurs in nuclei with positive decay energy. It is difficult for the cluster emission to occur because, the alpha emission is found to be preferred decay owing to its high branching ratio and it makes the cluster decay a unique process.

1.4 Applications of radioactive isotopes

Besides the use of naturally available radioactive isotopes, several isotopes have been produced artificially. Many isotopes have been used as gauge for thickness measurement. Based on the penetration power of the radiation, a device has been designed to measure the thickness of the materials kept in between the source and detector, which relies on the rate of change of count on the detector. The radioisotopes are used in different types of measuring gauges, level indicators and other devices. The radioisotopes which are emitting alpha particles are used as a source, such as in air crafts as a fuel by converting heat energy into electrical energy, smoke detector, pacemaker battery, in remote sensing, oil well boring equipment and for power generation in remote areas [30]. Beta particles are easily absorbed by materials depending on their thickness. The β – thickness gauge is used to measure the small thickness materials like photographic films by comparing the measured values with the standard values of the same materials.

γ - thickness gauge is used to find the large thickness materials. It is one-sided gauge which measures the thickness by detecting the backward scattered gamma rays and it is used for the measurement, where humans cannot access it. Nowadays, gamma rays or neutrons are used as radioactive borehole logging for the exploration of the oils and some other minerals present in the earth, based on the transmission of neutrons and gamma rays on different specimens or materials [30].

A special technique called tracer technique has been used for many purposes. In this method, the radioisotopes are used as the source and Geiger Muller (GM) counter is used for tracing its path. It used for the tracking of oxygen supply in lungs and also to identify the constriction in blood vessels. It is used in fertilizers which are absorbed by the plants from soil. The short-lived isotopes are used to track the uniformity in mixtures of ingredients such as chocolate mixtures, fertilizers, soap, shampoos and also in tablets. Various radioisotopes have been used in medical fields for different purpose. Those isotopes are categorized under radiopharmaceuticals. The technique in which the radioisotopes are injected into human body to examine the specific activity of the organs are called scintigraphy. In this method, isotopes of iodine, phosphorous, technetium, barium, etc., are used to examine the various parts like kidney, liver, heart, brain, blood vessels. It is also used to treat cancers and tumours and also to sterilise the medical equipment [30].

1.5 Nuclear models

In order to obtain a clear idea about the properties of the nuclei, it is significant to study more about inter nucleon interaction. Difficulty arises from mathematical treatment of many-body problem as well as from the tendency of the nuclear force itself. To overcome these difficulties, many approaches have been adopted. These approaches can be treated mathematically and able to account for at least a few nuclear properties. It can be improved by the addition of new terms to obtain the expected results. Different types of models have been proposed for the nucleus. Basically, nuclear models are classified into two types, namely independent particle model and collective model, as shown in Fig. 1.2.

Fermi gas model: Generally, Fermi gas model is known as the statistical model of an atomic nucleus. It is assumed that the nucleus is having a degenerate gas of nucleons like electrons in metals. In accordance with Pauli's exclusion principle, all the nucleons are allowed to occupy the lowest possible states. The protons and neutrons are called as fermions which are having half-integral spin. Their behaviour has been determined using Fermi-Dirac statistics. All the particles are allowed to occupy upto a maximum energy called Fermi energy. The

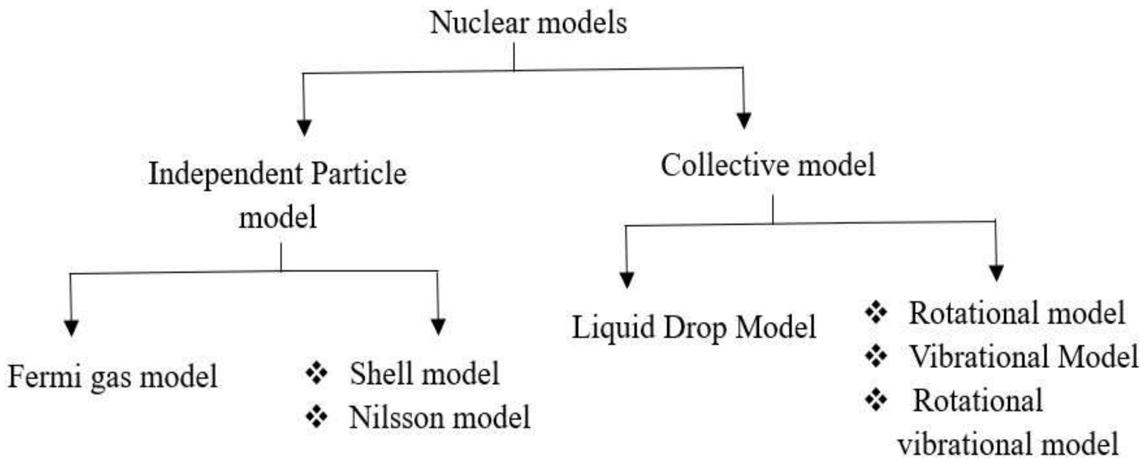

Figure 1.2: Classification of the nuclear models.

fermions are filled separately in the potential well with two particles having opposite spins in each energy level. The depth of the potential well for proton is probably less than the potential well for neutron. The neutron experiences only nuclear attractive forces but proton experiences Coulomb repulsive forces in addition.

The advantages of the Fermi gas model are its ability to predict the properties of the excited state of the nucleons and the unbounded states of the medium and heavy nuclei. There won't be even a small momentum transition between the nucleons, since all the low-lying states are completely filled. The excited states behave as a condensed state material than the ground state. The fermions no longer exist in the Fermi gas, as the interaction between them increases with increase in the excitation energy. The major drawback of this model is that, it is not able to estimate the characteristics of the low-lying states.

Liquid Drop Model (LDM): The constant nuclear density and constant binding energy per nucleon of the nucleus are the macroscopic properties which resembles like a drop of liquid. The characteristcics of the nucleus can be identified from its collective behaviour of the nucleons, when a strong short-range interaction occurs between them. The properties of the nucleus and the liquid drop are very similar. George Gamow [31] was the first to discover the liquid drop model and it was further improved by Neil's Bohr and Wheeler [32]. This model takes the collective behaviour of the nucleons into account. Hence, it is a statistical model. The nucleons within the nucleus are bound together tightly, whereas the outer nucleons are loosely bound. Based on this model, the nucleus was considered as an incompressible and charged liquid drop as there were many similarities between the nucleus and liquid drop. C. F. Von Weizsacker and H. A. Bethe [33] have developed semi-empirical mass formula for the calculation of binding energies of the nuclei. The mass of the atomic nucleus of an element having mass number A and atomic number Z, be calculated using the formula as follows:

$$M(A,Z) = ZM_p + NM_n - \frac{B(A,Z)}{c^2} \tag{1.1}$$

Here, M_p and M_n represent the mass of the proton and neutron respectively, where $B(A,Z)$ is the binding energy of the nucleus. The binding energy $B(A,Z)$ of the nucleus with mass number A and atomic number Z is calculated by the addition of number of terms as given below:

$$B(A,Z) = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_a \frac{(N-Z)^2}{A} + \delta \tag{1.2}$$

where

$$\delta = \begin{cases} +a_p \frac{1}{A^{3/4}} & \text{for} \quad \text{even-even} \quad \text{cases} \\ 0 \quad \text{odd-even} & \text{or} \quad \text{even-odd} \quad \text{cases.} \\ -a_p \frac{1}{A^{3/4}} & \text{for} \quad \text{odd-odd} \quad \text{cases} \end{cases} \tag{1.3}$$

Volume energy: The nuclear density of the nucleus with mass number A remains constant. Volume of the nucleus is directly related to the number of nucleons contained in it and it is reasonable to consider volume energy at which a_VA binds the nucleons inside the nucleus due to its internucleon interaction. The binding energy per nucleon indicates the volume energy coefficient a_V.

Surface energy: The nucleons that are lying on the surface or near to the surface experience less attractive forces whereas the nucleons lying deep inside the nucleus are strongly bound due to the neighbouring nucleons and completely experience a strong attractive force and therefore the binding energy is over approximated by the volume energy. Here, a_S represents the surface energy coefficient.

Coulomb energy: The nucleus is a positively charged liquid and due to the presence of positively charged protons, there exist a Coulombic repulsion. The nucleus is less tightly bounded and their contribution to the binding energy is negative. The Coulomb energy coefficient a_C is a proportionality constant.

Asymmetry energy: The nucleus with mass number A is assumed to be stable, when the energy of the nucleus is minimum and it can be achieved by filling the protons and neutrons in the energy levels in the order of increasing energies in accordance with the Pauli's exclusion principle. The nucleus with same number of Z and N is stable nucleus. In the case of unstable nuclei, when the neutron number exceeds and occupies the higher quantum energy states than the protons, the excess neutron try to reduce the binding energy. This effect is called as asymmetry energy. The excess of neutron or proton contributes a small amount to the binding energy, which results in the decrease of binding energies. This contributes to the asymmetry energy or neutron excess energy; it is proportional to the square of the neutron excess term and proportionality constant is a_a.

Pairing energy: The nuclei with even number of Z and N are stable nuclides and it provides positive contribution to the binding energy. The nuclei with even-Z and odd-N and vice versa, are said to have a moderate stability and there is no contribution to the binding energy. Those nuclei with odd-Z and odd-N are less stable and it provide negative contribution to the binding energy. It is mainly owing to pairing of spins. The paired spin of proton and neutron makes the nucleus more stable, whereas unpaired spins result in the unbound nucleus. Here, a_p represents the pairing energy coefficient.

Advantages of the Liquid Drop Model:

- It can be used to investigate nuclei that are in excited states. and can be used as a mechanism for low energy decay, to which this model is used as the frame work of compound nucleus theory.
- The theory of nuclear fission has been explained successfully.
- It is used to obtain accurate binding energies of the nuclei and also to study the properties of the isobars.

Limitations of liquid drop model:

- It was unable to clarify the extra stability of certain nuclei (i.e., the nuclei with magic numbers of N and Z).
- This model is not able to explain the independent behaviour of the nucleons in accordance with their spin, parity and their magnetic moments.
- Though this model is able to explain well about the medium mass nuclei, it fails to explain the light mass nuclei, where the nuclear surface effect dominated the Coulomb repulsion and the situation is vice versa for the case of heavy mass nuclei.
- This model fails to explain the closed shell effects caused due to the discontinuities at the same number of protons and neutrons.

Shell model: Though the liquid drop model is successful in describing the mass and binding energy of the nucleus, it was unable to clarify certain properties of the nuclei, this led to the evolution of shell model. Gapon and Dmitri Ivanenko [34] have discovered nuclear shell model by proposing an idea about the distribution of protons and neutrons in the nuclear subshells in the nucleus. This model is developed by solving the Schrödinger equation to analyse the characteristics of each independent nucleon inside the nucleus, which is similar to the role of Hartree-Fock theory in atomic physics. The experimental evidences have proved the existence of nuclear shells in the atomic nucleus. Ionization energy and separation energies of both proton and neutron increases with increase in proton and neutron, however shows a sharp dip at particular number of N and Z. This abrupt discontinuity shows the occupancy of shells. Another one is occurrence of sharp and discontinuous behaviour at particular number of N and Z in relation to the separation energies. This represents the occurrence of magic numbers. The magic number of protons and neutrons are 2, 8, 20, 28, 50, 82 and additionally 126 for the case of neutron. It is initially noted by Elsasser [35] and later it is confirmed by Maria Goeppert Mayer [36] and independently by Haxel, Jensen and Suess [37]. They have predicted that the nuclei with the magic numbers exhibit extra stability than their neighbouring nuclei.

1.5.1 Evidences for shell structure

- The nuclei with the magic numbers as Z and N are called singly magic or doubly magic nuclei and they are found to be extraordinarily stable.
- The minimal energy required to separate the protons and neutrons are called separation energy of protons and neutrons respectively. Therefore, extra energy is required to separate the protons and neutrons from the magic nuclei.
- The relative abundance of the naturally occurring isotopes is greater for the magic nuclei.
- The isotopes and isotones having magic numbers are more stable when compared with its immediate neighbouring nuclei.
- The three isotopes of lead such as ^{206}Pb, ^{207}Pb and ^{208}Pb ($Z = 82$) are the stable end product of three naturally occurring radioactive series.
- The stable nuclei have their first excited state with higher energies compared to other nuclei. The probabilities of neutron and proton capture cross sections for the nuclei with magic number of protons and neutron are low because of its completely filled outer shells.

- The electric quadrupole moment is found to be zero for the case of stable nuclei because of its sphericity. When Z and N goes on increasing, the electric quadrupole moment is found to increase from zero to maximum and then it decreases to zero for the next magic nuclei.

- The radioactive nuclei emitting alpha particles are found to have higher energies. When alpha decay energyy is plotted with respect to the mass number (A) of the parent nucleus, for a given Z, the alpha decay energy decreases and sudden discontinuity is noted at $N = 126$, which is being magic number. Similar discontinuities are observed amongst the β-emitters at magic neutron and proton numbers [38].

1.6 Single Particle Energy

The sudden and discontinuous behaviour at some number of protons and neutrons shows the existence of shell closure at magic numbers of the nuclei. It is essential to consider the appearance of the nuclear potential well in the nucleus, where the protons and neutrons are arranged separately. In quantum mechanics, it is assumed that there exist a number of discrete quantum states in a bounded system. The nuclear shell structure is evolved on the assumption of spherically symmetric central field which determines the motion of each nucleon separately. Each nucleon tends to move in the potential well generated by other nucleons and each nucleon are filled in the orbit, in accordance with Pauli's exclusion principle.

Various potentials have been considered for the calculation of the nuclear energy levels such as infinite square well, harmonic oscillator potential well, etc. The degeneracy of each level is said to be $2(2l + 1)$ which represents the number of protons and neutrons that can occupy each level and the factor 2 and $(2l + 1)$ arises from the spin (m_s) and orbital (m_l) magnetic quantum numbers respectively. With n being the principal quantum number, the number of levels count are being labelled by l. Both these potentials are able to reproduce only the first three traditional magic numbers such as 2, 8, 20. To overcome this difficulty, an intermediate potential having a shape in between the infinite square well and harmonic oscillator potential called as Woods-Saxon potential is considered. The potential well depth is modified to arrive at accurate separation energies and it is observed to be in the order of 50 MeV. This potential is used to remove the degeneracy of the major shells. Degeneracy is defined as the quantum mechanical system having same energy in two or more states. The splitting of the energy levels becomes more complex and the gap between the shells increases, as we go higher. After filling the nucleon in accordance to degeneracy, only the first three magic numbers can be reproduced.

1.7 Spin-orbit splitting

After many attempts done by adding various parameter to the Woods-Saxon potential, a proper separation of the subshells has been achieved by Mayer [39] and independently by Haxel, Jensen and Suess in 1949 [40], by incorporating the spin-orbit coupling $l.s$ by borrowing the idea from atomic physicists. However, in atomic physics, the fine spectral lines are generated by the electron's electromagnetic moment in the magnetic field, when an electron move towards the nucleus. In nucleus it is assumed to have spin-orbit force which are not created by the electromagnetic field as in atoms. Here, the spin-orbit force has been incorporated to reproduce the observed magic numbers and it is considered to appear from the force due to nucleon-nucleon interaction. Here, the degeneracy with respect to spin magnetic moment is removed. The energy splitting increases with increasing l. The spin-orbit potential is considered to be of the form V_{so}. The expression for spin-orbit interaction energy is included via the constant c, whose value is given by $\sim$ -0.1 $\hbar\omega$. This is multiplied by $< l.s >$. The values of $< l.s >$ is $\frac{1}{2}l$ for $j = l + \frac{1}{2}$ and $-\frac{1}{2}(l+1)$ for $j = l - \frac{1}{2}$. Therefore the member of pair with higher j is shifted downwards and the member with lower j is shifted upwards and therefore a bunch of levels with larger gap between the shells. Thus, it reproduces the magic numbers properly and it is depicted in Fig. 1.3 [41], using harmonic oscillator potential.

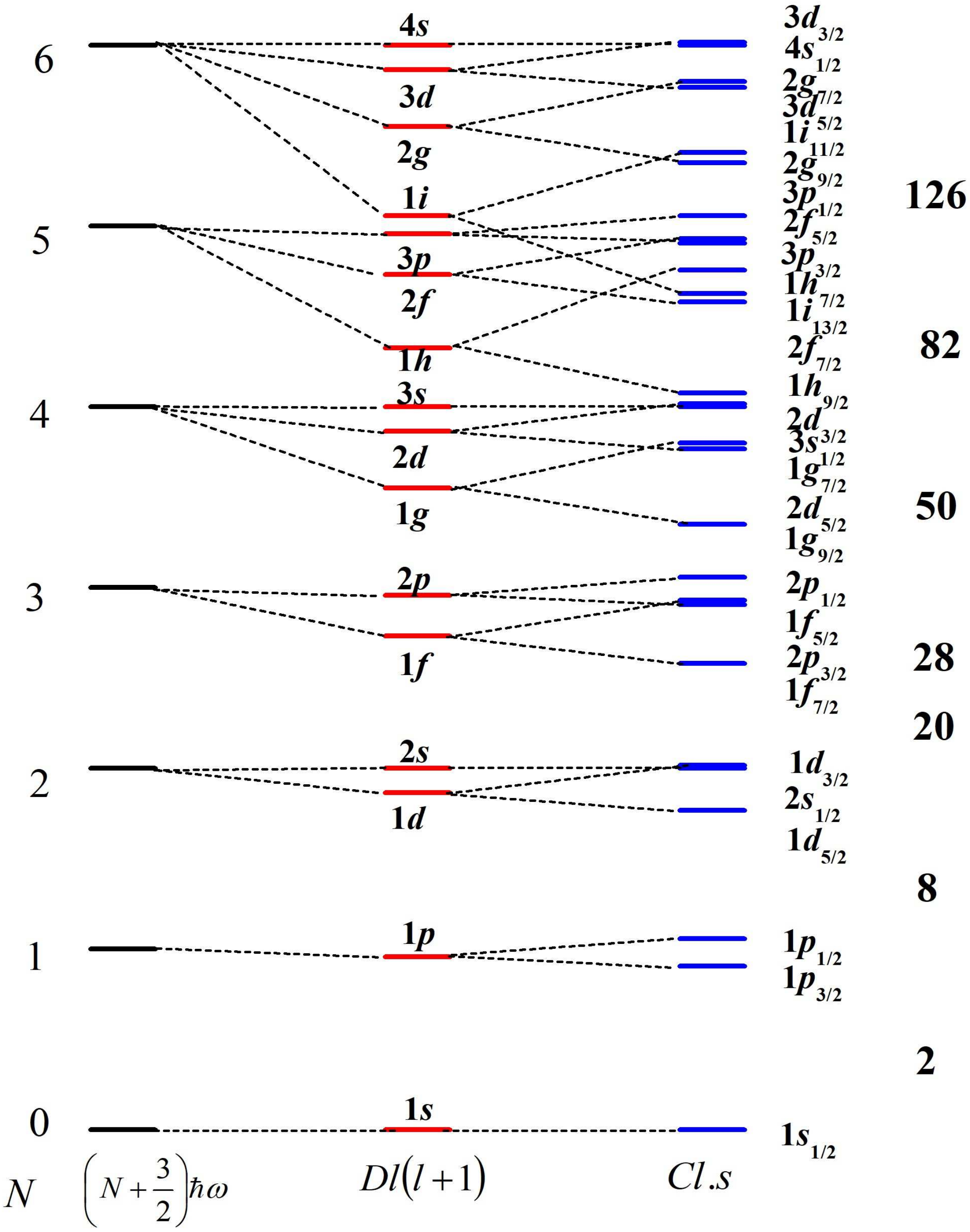

Figure 1.3: Single particle energy levels scheme

Evolution of new magic numbers: In last two decades, the evolution of new magic numbers near the proton and neutron dripline have made contribution in the field of nuclear physics in theoretical as well as in experimental studies. Especially for the nuclei lying in exotic region, increase in nucleon number lead to the steep decrease in the strength of the spin-orbit interaction, which in turn lead to changes in the ordering of the energy levels and so the magic numbers changes in the exotic region [42]. In addition to the doubly magic nucleus or singly magic nucleus, particularly the oxygen isotopic chain lying beyond the proton dripline, there exist a large subshell gap at $N = 14$ and 16 and $Z = 14$. The proton-rich or neutron-rich nuclei which are lying far from the stability line have prompted both theoretical and experimental investigation for the study of both fading away of established magic numbers and the emergence of new magic numbers beyond the nuclear dripline [43]. The appearance of new magic number such as $N = 32$ and 34 has been reported in the study of ^{54}Ca lying in the exotic region [44].

The search of the superheavy elements was started in late 1960's after the prediction of island of stability [45]- [51]. The super heavy elements with Z > 104 do not undergo fission due to its negligible fission barrier based on the liquid drop model. But these nuclei are said to have shell effects and they do exist. The overall energy of these nuclei is the addition of the macroscopic binding energies and the microscopic shell correction. For nearly three decades various macroscopic-microscopic (MM) models have been used for the theoretical studies of superheavy elements. Using this method, the $Z = 114$ and $N = 184$ is predicted to be the next magic number for protons and neutrons after the traditional magic numbers $Z = 82$ and $N = 126$. Many theoretical models have been used for the prediction of new magic numbers $Z = 92$, 114, 120 and 126 for protons and $N = 152$, 162, 164 and 184 for neutrons lying in superheavy nuclei mass region, in both structural and decay studies [52]- [59].

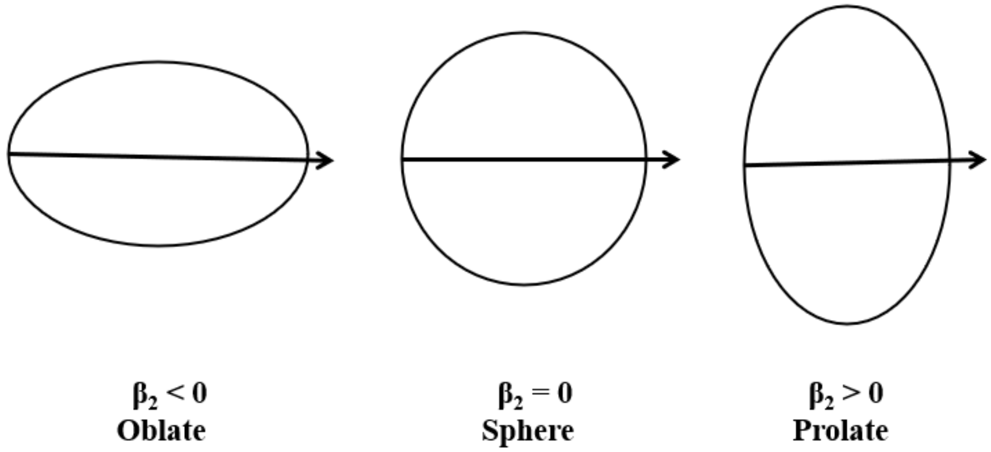

Figure 1.4: Schematic representation of the fission axis in spherical and deformed nuclei

1.8 Nuclear deformations

The nuclei lying in the mass region A < 150 are found to have one type of properties whereas the nuclei lying with the mass region 150 < A < 190 are found to be quite different. The nuclei in the mass region A < 150 are treated with a model having vibrational behaviour with spherical shapes, whereas the nuclei in the mass region 150 < A < 190 are treated to have rotational properties with deformed shape. The nuclei are having two types of collective motions namely, vibration and rotation. It is often mentioned as liquid drop model, since the nucleus seems to be a drop of liquid.

The nuclear rotational motion can be seen in the nuclei having non-spherical shapes and they have distorted from the spherical shape and are called as deformed nuclei. It usually occurs for the nuclei with the mass region 150 < A < 190 and A > 220. These deformed nuclei are commonly represented as elliptical in revolution. The nuclear quadrupole deformation (often denoted by β_2) refers to a measure of the deviation from a perfect shape of a nucleus. It quantifies how much the nucleus is elongated (prolate) or flattened (oblate) compared to a spherical shape. The quadrupole deformation is associated with the expansion of the density distribution in spherical harmonics. It is of two types, they are prolate spheroid and oblate spheroid. If $\beta_2 > 0$, the nucleus is said to be prolate spheroid whereas if $\beta_2 < 0$, it is said to be oblate spheroid in which the nucleus look like flattened. Fission axis typically refers to the specific axis or direction within the nucleus along which the splitting of the nucleus occurs. This axis can be influenced by the shape of the nucleus (which can be elongated or spherical). This is schematically represented in Fig. 1.4.

1.9 Superheavy elements

Till 1940, Uranium is the heaviest known element and is found abundant in nature. After 1940, about 26 elements have been synthesized in the laboratory. Investigation on superheavy elements (SHE) and its decay properties is one of the rapidly growing fields in nuclear physics. The quest for SHE has been accelerated since the prediction of island of stability [60]- [65]. The heaviest known completely filled stable nucleus in nature is the doubly-magic ^{208}Pb. The heaviest transuranium elements synthesized in the laboratory have very short half-lives. Owing to the increased Coulombic repulsion between the protons, they decay either by the emission of alpha particles or may undergo spontaneous fission. In accordance with liquid drop model, these heavier elements are unstable against spontaneous fission and it does not exist. In late 1960s, the concept of stability has been proposed and explained based on the concept of nuclear shell model, in which the nucleus is comprised of shells.

Based on the nuclear shell model, protons and neutrons are filled in the subshells and the nuclei with the completely filled shells have higher binding energy. It remains stable in the island of stability and have longer life-time compared to its adjacent nuclei. According to LDM, nuclei lying beyond $Z = 104$ have very slight fission barrier but they do exist due to their shell effects. The overall energy of the nucleus is approximated using the addition of macroscopic binding energy, microscopic shell correction and the effects of shell which is calculated using shell correction method. For past three decades, various theoretical models have been used to investigate the superheavy mass region. Beyond the established magic numbers Z = 82 and N = 126, there exist centre for stability in the superheavy mass region at Z = 114 and N = 184. Various theoretical studies have been done and arrived at new magic numbers in the superheavy mass region and they are Z = 114, 120 and 126 and N = 152, 162, 164 and 184.

Superheavy elements are synthesized in laboratories with the use of different heavy-ion accelerator techniques, around the world. Few laboratories which involve in the synthesis of SHE are namely, GSI Helmholtz centre for heavy ion research at Darmstadt, Germany, Lawrence Berkeley National Laboratory (LBNL) in US, Joint Institute of Nuclear Research (JINR) in USSR, and Institute of Physical and Chemical Research (RIKEN) in Japan. SHE are synthesized using two different fusion evaporation reactions and they are cold fusion reaction [66] and the hot fusion reaction [67]. In cold fusion reaction, Pb or Bi is used as target material and neutron-rich isotopes as projectiles and their excitation energy is low. But in hot fusion reaction, actinides are used a target material and ^{48}Ca as projectile and their excitation energy is high. These two approaches demanded the setting up of new separator facilities and the development of new detection methods. The cold fusion reaction, (mainly performed at GSI and RIKEN) led to the synthesis of elements with Z = 107 - 113 and the hot fusion reaction, (mainly performed at JINR-FLNR) led to the synthesis of elements up to Z = 118.

1.10 Objectives

The objectives of this thesis are to study the evolution of magic numbers and exotic decay modes such as two-proton emission and one-proton emission of nuclei in light, medium, heavy and superheavy mass region of the nuclear chart. An attempt is made to describe binding energies using Yukawa-plus-exponential mass formula (temperature independent) and nuclear exotic decays using Coulomb-plus-Yukawa-plus-exponential model with and without the incorporation of deformation. The objectives are listed as follows:

- To determine the single particle energies (SPE) from macroscopic binding energies using temperature-independent Yukawa-plus-exponential mass formula (YEM) and to determine spin-orbit splitting of protons and neutrons and also to extend the formalism to identify the emergence of new magic numbers in both light mass and superheavy mass regions.
- To study two-proton ($2p$) emission of experimentally identified nuclei using Coulomb-plus-Yukawa-plus-exponential model (CYEM) and to predict new $2p$ emitters.
- To incorporate deformation in CYEM, to study deformed $2p$ emitters.
- To determine half-lives of one-proton ($1p$) emission of experimentally identified nuclei within Cubic-plus-Coulomb-plus-Yukawa-plus-exponential model (CCYEM), for both spherical and deformed $1p$ emitters. To predict new $1p$ emitters and also to find competing alpha decay of proton emitters.