INTRODUCTION

CHAPTER I

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1.1 Nuclear physics:

Nuclear physics is a branch of Physics which deals with the study of atomic nuclei and the understanding of potential ways in atomic nuclei. The most commonly known applications of nuclear physics are nuclear power generation. But the research has provided application in many fields, including those in nuclear medicine and magnetic resonance imaging, ion implantation in materials engineering, and radiocarbon dating in geology and archaeology.

1.2 Radioactivity:

The phenomenon of spontaneous emission of highly penetrating radiations from heavy elements of atomic weights greater than about 206, occurring in nature is called natural radioactivity. The elements which exhibit this property are called radioactive elements. The atoms of radioactive elements emit radiations composed of three distinct kinds of rays (α, β and γ). In the process, the elements break up, leading to an irreversible self-disintegration [1].

1.3 Basic decay modes:

The basic decay modes are classified in to three types. They are

- Alpha decay (α)
- Beta decay (β)
- Gamma decay (γ)

1.3.1 Alpha Decay:

In a series of seminal experiments by Ernest Rutherford and his collaborators in 1988 established the important features of alpha decay. The behavior of the radiations from natural sources of uranium and thorium and their daughters was studied in magnetic and electric field. Alpha decay occurs when the nucleus of an atom spontaneously ejects an alpha particle. The alpha particle is the same as a helium nucleus with 2 protons and 2 neutrons. This means the number of protons in the nucleus is reduced by 2 and the total number of nucleons is reduced by 4 [2].

$$^{238}_{92}U --------> ^{234}_{90}Th + \alpha$$

The reason for alpha decay to occur is, the nucleus has too many protons which cause excessive repulsion. In an attempt to reduce the repulsion, a helium nucleus is emitted. The way it works is that the helium nuclei are in constant collision with the walls of the nucleus and because of its energy and mass; there exists a nonzero probability of transmission. That is, an alpha particle (helium nucleus) will tunnel out of the nucleus. Alpha decay occurs only if it is energetically allowed, i.e., the Q-value is positive.

$$Q_{\alpha} = \left[M(A, Z) - M(A-4, Z-2-M) - \left({}^{4}_{2}He \right) \right] c^2 > 0$$

The Q-value of alpha decay is the total available energy, which gets divided into the kinetic energies of the daughter and the alpha-particle (for decay from ground state to ground state). Therefore,

$$Q = K_D + K_{\alpha} = K_{\alpha}\left(\frac{A}{A-4} \right)$$

Where K_D and K_{α} is the kinetic energies for daughter nuclei and alpha particle. And A represents the mass number.

Two important features of alpha decay are that the energies of the alpha particle are known to generally increase with the atomic number of the parent but yet the kinetic energy of the emitted particle is less than that of the Coulomb barrier in the reverse reaction between the α particle and the daughter nucleus. In addition, all nuclei with mass numbers greater than A»150 are thermodynamically unstable against alpha emission (Q is positive) but alpha emission is the dominant decay process only for the heaviest nuclei, A>150. The energies of the emitted alpha particles can range from 1.8 MeV (^{144}Nd) to 11.6 MeV (^{212}Po) with the half-life of ^{144}Nd being 5×10^{29} times long as that of ^{212}Po. Typical heavy element alpha decay energies are in the range from 4.9 MeV. Alpha rays are composed of heavy helium nuclei, so their velocity is quite weak as is their penetration in matter.

1.3.2 Beta Decay:

Beta decay refers to the spontaneous radioactive decay where a beta particle is produced. There are two types of beta decay where the beta particle is either an electron or a positron. In general, the nuclear β decay can be denoted by

$$A\ (Z, N) \text{ -------------}\rightarrow A\ (Z+1, N) + e^{-} + \overline{\gamma_e}\ ,$$

$$A\ (Z, N) \text{ -------------}\rightarrow A\ (Z-1, N) + e^{+} + \gamma_e$$

Where the nucleus of mass number A consisting of 2 protons and N neutrons is transformed in to a nucleus of Z$\pm$ 1, N protons and neutrons by the emission of β particle [3].

1.3.3 Gamma Decay:

Most α and β decays, and infact most nuclear reactions as well, leave the final nulceus in an excited state. These excited states decay rapidly to the ground state through the emission of one or more γ rays, which are photos of electromagnetic radiation like X rays or visible light [4].

$$^{A}_{Z}X \text{ - - - - - - - - - ->}\ ^{A}_{Z}X$$

1.4 Nuclear Reactions:

A nuclear reaction is semantically considered to be the process in which two nuclei, or else a nucleus of an atom and a subatomic particle (such as a proton, neutron, or high energy electron) from outside the atom, collide to produce one or more nuclides that are different from the nuclide(s) that began the process. Thus, a nuclear reaction must cause a transformation of at least one nuclide to another. This is called a nuclear reaction. Nuclear reaction used to study the behavior in the relation with the other subatomic particles. Study of nuclear reaction provides considerable information of nuclei as well as on the nature of their interaction [5].

1.4.1 Types of Nuclear reactions:

- Direct Reactions
- Capture Reactions
- Compound Reactions
- Spallation Reaction

- **Direct Reactions:**

The direct Reactions are the one which proceeds without the intermediate step of formation of the compound nucleus. Direct reactions are considered to be instantaneous processes and take place only at the surface of the target nucleus and therefore direct reactions products exhibit certain characteristics which are markedly different from those if the reaction proceeds by way of compound nucleus formation [5].

The direct reactions includes

1. Elastic Scattering
2. Inelastic Scattering
3. Knockout Reactions
4. Stripping Reactions
5. Pick up reactions

Elastic Scattering:

It is a process in which the incident and the outgoing particles are the same and the kinetic energy is conserved. Thus if the incident particles and the target nuclei are simply scattered by each other without any change in their relative energy, the process is said to be elastic scattering [5].

Inelastic Scattering:

The bombarding may result in to a change in the relative energy without change in the internal structure of the target nucleus. This type of process is called Inelastic scattering [5].

Knock out Reactions:

Knock-out reaction, where the incident particle (generally a nucleon) picks up a particle of the target nucleus and continues on its path, resulting in three reaction products [5].

Stripping reactions:

An incident deuteron comes close enough to a target nucleus for one of its two constituent nucleons to settle in the nucleus while the other continues way though along a different direction [5].

Pick up reactions:

An incident nucleon comes enough to a target nucleus, pickups nucleon from the nuclear surface and the two come together as deuteron. The inverse of stripping reactions is called pick up reaction [5].

- **Capture Reactions**

  Both charged and neutral particles can be captured by nuclei. Neutron capture reactions are used to produce many radioactive nuclides [5]. For example,

  $^{197}Au\ (p, \gamma)\ ^{198}Hg$

  $^{238}U\ (n, \gamma)\ ^{239}U$

- **Compound Nuclear reaction:**

Either a low energy projectile is absorbed or a higher energy particle transfers energy to the nucleus, leaving it with too much energy to be fully bound together. On a time scale of about 10^{-19} seconds, particles usually neutrons are "boiled" off. That is, it remains together until enough energy happens to be concentrated in one neutron to escape the mutual attraction. Charged particles rarely boil off because of the coulomb barrier. The excited quasi-bound nucleus is called a **compound nucleus.**

- **Spallation Reactions:**

A nuclear reaction that can take place when two nuclei collide at very high energy (typically 500 MeV per nucleon and up), in which the involved nuclei are either disintegrated into their constituents (protons and neutrons), light nuclei, and elementary particles, or a large number of nucleons are expelled from the colliding system resulting in a nucleus with a smaller atomic number. This mechanism is clearly different from fusion reactions induced by heavy or light ions with modest kinetic energy (typically 5 MeV per nucleon) where, after formation of a compound nucleus, only a few nucleons are evaporated. A spallation reaction can be compared to a glass that shatters in many pieces when it falls on the ground. Spallation has two stages: intra-nuclear cascade and deexcitation.

1.4.2 Compound Nucleus formed in low energy Heavy –Ion reactions:

Compound Nucleus:

The compound nucleus theory of nuclear reaction was put forward by N.Bohr in 1936. Prior to the publication of this classic paper, attempts were made to explain the variation of neutron cross sections on the assumption that the incident projectile particle interacts with a simple square well type potential. This problem is easily handled with in scattering theory in Quantum mechanics and calculations predict that an interaction with a square interaction with a square potential well can neither change the energy of the particles nor can remove it from the beam, it can only deflect it.

Bohr's compound nucleus theory:

According to Bohr's compound nucleus theory, the nuclear reaction is a two stage process as outlined below:

- ✓ A low energy bombarding particle is absorbed by the target nucleus and both together from a compound nucleus which is in a highly excited state, i.e. incident particle combined with the target particle to give compound nucleus. The kinetic energy of the incident particle together with its binding energy with the compound nucleus represents the excitation energy of the compound nucleus. After the incident particle has merged completely with the target nucleus, its energy no longer remains concentrated on one particle but its rapidly shared by the collective motion of all the particle of the new system-compound nucleus. Thus each of the nucleons in the compound nucleus will have some additional energy but none of them will have the likelihood of getting all the energy of the incoming particle or even any large fraction of it. Because of this thorough sharing of energy among all the nucleons, the compound nucleus has no chances of immediate break up

- ✓ The second stage in the compound nucleus theory involves the break-up of the compound nucleus in to a product nucleus and one or more emitted particles.

Compound nucleus-------→product nucleus + emitted particles.

The decay of the compound nucleus will occur only when sufficient energy gets concentrated on some single nucleon or group of nucleons such as the alpha particles, for it to break through the coulomb potential barrier and escape from the nucleus. As the life time of the nucleus is larger on a nuclear scale the intrinsically slow process of electromagnetic radiation (γ - emission) competes strongly with charged particle emission. Since the de-excitation of the compound nucleus is completely independent of the mode of its formation. i.e. the break up does not take place until the compound nucleus has completely forgotten its history of formation. In general, the emitted particle is different from the one which entered the target nucleus to form the compound nucleus and it will neither have the energy nor the direction of the incoming particle. However, even if the emitted particle is the same as the incident projectile particle; e.g. a neutron escapes when a neutron enters the process need not be an elastic collision. Let us consider an equation.

$$\sigma(a,b) = \sigma_c(a)G_c(b)$$

where σ_c is the cross section for the formation of the compound nucleus C by the incident particle 'a' with the target nucleus X and G_c is the relative probability that the compound nucleus C, once formed decays with the emission of the particle 'b' leaving a residual nucleus Y. Probability G_c(b) is also referred to as the branching ratio of the reaction in to the emission of 'b' and it is a pure number. It is implied that the particle 'a' and the target nucleus are in a given total angular momentum states specified by the symbol 'a' and that the emission of the particle 'b' leaves the residual nucleus in a given state. During the reaction, total angular momentum and parity were conserved. The specified entrance and exit states were called channels. In this terminology, the reaction is initiated through the channel 'a' and the compound nucleus decays through the channel 'b'. According to Bohr's assumption, the disintegration of the compound nucleus in to different channels depends only upon the excitation energy [5].

1.5 Nuclear Models:

In the absence of the detailed theory of nuclear structure many attempts have been made to correlate nuclear data in terms of various models. Several models have been proposed, each based on a set of simplifying assumptions and useful in a limited way. Each model serves to correlate a portion of the experimental knowledge about the nuclei, usually within a more or less narrow range of phenomena, but fails when applied to data outside the range. Each of the models is based on a plausible analogy that correlates a large amount of information and enables predictions of the properties of nuclei. Nuclear models can be classified into two main groups [2]. They are

- Liquid drop model
- Independent particle model or Shell model
- fission models
- Cluster models

1.5.1 Liquid drop Model:

Liquid-drop model describes the atomic nuclei which are formulated in 1936 by Neil Bohr and used (1939) by him and John A. Wheeler to explain nuclear fission. According to the model, the nucleons (neutrons and protons) behave like the molecules in a drop of liquid. If given sufficient extra energy (as by the absorption of a neutron), the spherical nucleus may be distorted into a dumbbell shape and then split at the neck into two nearly equal fragments, releasing energy. Although inadequate to explain all nuclear phenomena, the theory underlying the model provides excellent estimates of average properties of nuclei [2].

1.5.2 Independent particle model or shell model:

Shell nuclear model, describes of nuclei of atoms by analogy with the Bohr atomic model of electron energy levels. It was developed independently in the late 1940s by the American physicist Maria Goeppert Mayer and the German physicist J. Hans D. Jensen, who shared the Nobel Prize for Physics in 1963 for their work. In the shell nuclear model, the constituent nuclear particles are paired neutron with neutron and proton with proton in nuclear-energy levels that are filled, or closed, when the number of protons or neutrons equals 2, 8, 20, 28, 50, 82, or 126, the so-called magic numbers that indicate especially stable nuclei. The unpaired neutrons and protons account for the properties of a particular species of nucleus as valence electrons account for the chemical properties of the various elements. The shell model accurately predicts certain properties of normal nuclei, such as their angular momentum; but for nuclei in highly unstable states, the shell model is no longer adequate and must be modified or replaced by another model, such as the liquid-drop model, collective model, compound-nucleus model, or optical model [2].

1.6 Fission models:

Fission model includes:

- ✓ unified fission model
- ✓ Numerical super asymmetric fission model
- ✓ Analytical super asymmetric fissionmodel

1.6.1 Unified fission model:

The Gamow's theory of alpha decay is based on the concept of a preformed alpha particle tunneling through a coulomb barrier which is due to the alpha- particle and the daughter nucleus considering a one dimensional WKB penetration problem through a coulomb plus the square well nuclear potential of width

$$R = r_0[A_1^{1/3} + A_2^{1/3}]$$

The decay constant λ_G is defined as $\lambda_G = \nu_0 P$

Where ν_0 represents the escape frequency with which the alpha particle bombarded the barrier. The penetration probability P, for the available Q – value can be calculated by using the WKB approximation [44]. The half-life times $T_{1/2}$ are related to decay constant λ as

$$\lambda = \frac{\ln 2}{T_{1/2}}$$

The existing theoretical models for explaining new cluster decay process have made the modification of taking more realistic nuclear potentials, instead of the square well potential used by Gamow. In the unified fission models the alpha particle and the clusters are considered to be preformed with equal probability (i.e.) P_0 =1, so if P is the barrier penetrability, the decay constant in UFM is given as

$$\lambda^{UFM} = \gamma_0 P$$

where P is the barrier penetrability for the given form of the potential V(r). The form of the potential V(r) differs from one model to another.

The barrier penetrability is given as

$$P = \exp(-2K)$$

$$K = \frac{1}{\hbar} \int_{R_a}^{R_b} [2\mu[V(r)] - Q]^{1/2} \partial r$$

Where R_a & R_b are both the inner and outer turning points.

$$V(R_a) = V(R_b) = Q$$

The form of potentials V(r) differs from one model to another. In some cases for alpha decay the V(r) =E(R) for $r \geq R_1 + R_2$, where as in other models,

$$V(r \geq R_t) = E_c(r) + V_N(r)$$

R_t is the touching configuration radius. The nuclear potential is added to the coulomb potential even for $r \geq R_t$

The assault frequency ν_0 is defined differently in different UFM's. Generally it is associated with the zero point vibration energy E_v as

$$\nu_0 = \frac{\omega}{2\pi} = \frac{E}{h}$$

With E_v obtained either empirically or in the harmonic oscillator of the potential in the region $R_0 \leq r \leq R_t$

$\omega = \sqrt{C/M}$ where M is the potential nuclei and C is the stiffness of the oscillator.

In unified fission model there are two types namely

1. Numerical super asymmetric fission model (NSAFM)
2. Analytical super asymmetric fission model (ASAFM)

1.6.2 Numerical Super Asymmetric Fission Model (NSAFM):

To estimate the half-lives based on the fission mechanism, a Numerical Super Asymmetric fission Model was developed which was derived by extending three variants of the liquid drop model, and Yukawa-plus exponential model to the systems with charge asymmetry different from the mass asymmetry and by using a phenomenological shell correction [6].

1.6.3 Analytical Super Asymmetric Fission Model (ASAFM):

The first predictions of the nuclear lifetimes against spontaneous cluster emission by using ASAFM, developed as of 1980 by Poenaru [6]. This model estimates the half –lives and branching ratios relative to α decay for more than 150 decay models, including all cases, experimentally confirmed to date on ^{14}C, $^{24\text{-}26}Ne$, $^{28\text{-}30}Mg$ and ^{32} Si radio activities. It has been improved by incorporating the even-odd effect and the variation of the correction energy with the mass number, A_e of the emitted cluster for $A_e > 24$. Recently, the ASAFM half-life calculations have been extended to the regions of nuclei far from stability and super heavies, with the 1988 mass tables as input data [6].

1.7 Cluster models:

In cluster model it is said that clusters of different sizes have different probabilities of their being preformed in parent nucleus. Cluster formation probability is determined by the overlap of the wave function of the parent nucleus with those of both fragments described by so called spectroscopic factor. Some examples of Cluster Model are

1. Preformed cluster model
2. Dynamical cluster decay model

1.7.1 Preformed Cluster model:

The effects of shell closure in nuclei via cluster decay have been investigated. In Preformed Cluster Model (PCM) based on Quantum Mechanical Fragmentation Theory, the key point in the clusters preformationof radioactivity which involves the interplay of close shell effects of parent and daughter nucleus. Small half-life for a parent indicates shell stabilized daughter and long half-life indicates the stability of the parent against the decay.

1.7.2 Dynamical cluster decay model:

It is developed further for the decay of hot and rotating compound nuclei [CN] formed in light heavy-ion reactions. The model is worked out in terms of mass and charge asymmetry, neck-length parameter, which is related to the total kinetic energy TKE (T) or effective Q value $Q_{eff}(T)$ at temperature T of the hot compound nuclei and is defined in terms of the compound nuclei binding energy and ground-state binding energies of the emitted fragments. The emission of the both the light particles (LP), with $A \leq 4, Z \leq 2$ as well as the complex intermediate mass fragments (IMF), with $4 \leq$ A<20, Z<2, is considered as the dynamical collective mass motion of preformed clusters through the barrier. Within the same dynamical model treatment, the light particles are shown to have different characteristics compared to those of the intermediate mass fragments.

1.8 Applications of Nuclear reactions:

- To produce new nuclides or elements,
- Release energy and to produce subatomic particles.
- To do scientific investigations,
- used in engineering projects,
- medical diagnose and treatments

1.9 Applications of nuclear models:

- A nuclear model is simply a way of looking at the nucleus that gives a physical insight into as wide a range of its properties as possible. The usefulness of a model is tested by its ability to provide predictions that can be verified experimentally in the laboratory.
- Nuclear model, any of several theoretical descriptions of the structure and function of atomic nuclei (the positively charged, dense cores of atoms).

2.0 Applications of Alpha decay:

Alpha decay are used in various fields such as,

- Cancer Treatment
- Heating Devices
- Remote Sensing Stations
- Smoke Detector
- Seismic and Oceanographic Devices

- **Cancer Treatment:**

Alpha radiation is used to treat various forms of cancer. This process, called unsealed source radiotherapy, involves inserting tiny amounts of radium-226 into cancerous masses. The alpha particles destroy cancer cells but lack the penetrating ability to damage the surrounding healthy cells.

- **Heating Devices:**

Alpha radiation is used to provide heating for spacecraft. Unlike radioisotope thermoelectric generators that convert heat to electricity, radioisotope thermal generators make direct use of the heat generated by alpha decay.

- **Remote Sensing Stations:**

The Unites States Air Force uses alpha radiation to power remote sensing stations in Alaska. Strontium-90 is typically used as the fuel source. These alpha-powered systems enable unmanned operations for long periods of time without the need for servicing.

- **Smoke Detector:**

Alpha radiation is used in some smoke detectors. The alpha particles from americium-241 bombard air molecules, knocking electrons free. These electrons are then used to create an electrical current. Smoke particles disrupt this current, triggering an alarm.

- **Seismic and Oceanographic Devices:**

Alpha radiation is also used to power a wide array of seismic and other oceanographic devices. These unmanned devices are often located in isolated locations, such as on the ocean floor, which limits the practicality of short-term batteries. Strontium-90 is the most common material used in these alpha decay batteries.

2.1Applications of Nuclear physics:

A general application of nuclear physics refers to both applications as a result of nuclear physics and applications which employ nuclear physics. An example of the former would be medical imaging. Had there never been any sort of thing known as nuclear physics, we wouldn't need imaging techniques to scan the body for radiation. An example of an application employing nuclear physics would be radioactive dating. The radioactive properties of certain elements are used in order to determine the age of something.

- **Medical Imaging**: (such as CAT scans and MRI) is used to determine the amount of radiation a person has been exposed. There have been quite a few different techniques and more are still being developed and improved presently.
- **Radio carbon dating**: uses radioactive properties of certain elements to determine the age of something such as an ancient person.

- **Radiation Detection**: involves different instruments used in order to detect radiation present somewhere.

2.2 Objectives of study:

For the present study two problems are considered. One is the study on alpha decay and the other is the de-excitation of compound nucleus formed in heavy-ion reaction. The objectives are:

- To study the characteristics of alpha decay of even-even, even-odd, odd-even nuclei of heavy and superheavy nuclei using modified unified fission model.
- To study the de-excitation of the compound system of medium mass region, formed in the heavy- ion reaction. It is focused towards studying the cross sections of the compound nuclei $^{48}Cr^*$ formed in $^{24}Mg+^{24}Mg$ reaction with E_{cm}=4.4 MeV, by using DCM model.