Evaluation Of Reaction Cross-Section For Deuteron Induced Radioisotope (^{125}I,^{62}Zn,^{15}O And ^{103}Pd) At Different Energy Ranges Using the PACE 4 Code

By

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A THESIS PRESENTED TO

THE GRADUATE PROGRAMS OF COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES, ADDIS ABABA UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

MASTER OF SCIENCE in PHYSICS

ADDIS ABABA, ETHIOPIA

JUNE 2024

ADDIS ABABA UNIVERSITY

GRADUATE PROGRAMS

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Dated: June 2024

ADDIS ABABA UNIVERSITY

Date: **June 2024**

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Department: **Department of Physics**

Degree: **M.Sc.** Convocation: **July** Year: **2024**

Signature of Author

This Work is Dedicated
to Men and Women of Science who labored for the welbeing of all humanity.

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Acknowledgements

First of all I would like to thank the almighty **God** and His Holly mother **The Blessed Virgin Marry**, next I would like to extend my gratitude for my family members all around me who are my strength and courage leading me to this position.

My endless heart feel thankful goes to my advisor **Dr.Tilahun tesfaye** for his everlasting and remarkable advise, guiding, commenting and support on my research work. He is always on the bottom of My heart in gravitating me to study and love Nuclear physics.

My strong appreciation and respect goes to Physics Department of Addis Ababa University, all my instructors, and my staff members for facilitating conditions for my research work and material support.

Addis Ababa University

Anteneh Getachew Abeje

June 19, 2024

Abbreviations

PACE4	projectile angular momentum coupled evaporation code
CF	complete fusion
PET	positron emission tomography
MeV	mega electron volt
EFs	excitation functions
CN	compound nucleus
EC	Electron Capture
IAEA	International Atomic Energy Agency
LET	Linear Energy Transfer
ENDF	evaluated nuclear data file
SPECT	Single Photon Emission Computer Tomography
TENDL	Talys Evaluated Nuclear Data Library

Abstract

This thesis work emphasize on theoretical evaluating reaction cross sections of deuteron induced nuclear reactions for the production of therapeutic radionuclide using PACE4 statistical model code , which is a code based on the statistical model of nuclear reactions.

PACE4 statistical model code is used to calculate the theoretical nuclear cross section in the production processes of ^{125}I, ^{62}Zn, ^{15}O and ^{103}Pd, while experimentally decoded nuclear cross sections data of these radionuclide were taken from ENDF(Evaluated nuclear data file) IAEA database, to compute a reliable result, PACE4 statistical model code performed at level density parameter(K=8, K=10 and K=12) and the number of cascades(events in monte carlo calculation) is set at 100,000.

The target radioisotopes are ^{124}T, ^{63}Cu, ^{14}N and ^{103}Rh are taken for the production of medical useful radioisotope ^{125}I, ^{62}Zn, ^{15}O and ^{103}Pd respectively. Deuteron energies ranging from 4.5 MeV to 20 MeV were considered for the production of ^{125}I, 17 MeV to 35 MeV for the production of ^{62}Zn, 1 MeV to 20 MeV for the production of ^{15}O and energy range from 6.5 MeV to 23.5 MeV were considered for the production of ^{103}Pd, and then experimental and theoretical outputs of nuclear cross sections of these radionuclide production were analyzed and compared.

The maximum experimental and theoretical nuclear cross section computed at different energy range is stated below respectively: for ^{124}T (d,n)^{125}I reaction the maximum cross section at deuteron incident energy of 9.0 MeV was 232 mb and 555 mb at 9.5 MeV (at K=12), for ^{63}Cu(d,3n)^{62}Zn reaction 50.5 mb at 33 MeV and 63.9 mb at 31.5 MeV (at K=8), for the reaction ^{14}N(d,n)^{15}O the maximum cross section was 213 mb at 3.5 MeV and 214 mb at 12.5 MeV (at K=12) and for the reaction ^{103}Rh(d,2n)^{103}Pd the maximum cross section was 1056 mb at 13.5 MeV and 1390 mb at 18.5 MeV (at K=12).

The PACE4 code slightly gives good agreement with ENDF determined excitation function at some computed radionuclide production considered under this study,while the rest results are unfitted with the ENDF data. It has been observed that complete fusion, incomplete fusion and pre-equilibrium emission processes play important roles in heavy ion reactions at these energies. The observed disagreement may be credited to the contribution from the incomplete fusion reaction, pre-equilibrium emission processes and light particle reaction is not well taken into account by PACE4 statistical model code.

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The beginning of the nuclear physics may be traced back to the studies on atomic structure started with discovery of radioactivity in 1896 by Henry Becquerel or Rutherford's hypothesis of the existence of the nucleus in 1911, it is clear that the experimental and theoretical studies in nuclear physics have played a prominent role in the development of twentieth century physics. Thus nuclear physics can be regarded as the descendant of chemistry and atomic physics and in turn the progenitor of particle physics [1].

Once we have identified a nuclide,we can then set about to measure it's properties, are mass,radius,relative abundance,(for stable nuclide),decay modes,and half-lives(for radioactive nuclide),reaction modes and cross-sections,spin,magnetic dipole and electric quadrapole moments,and excited states.Thus far nuclide with 108 different atomic numbers(1 to 107)have identified;counting all the the different isotope's the total number of nuclide is well over 1000,and the number of carefully studied new nuclide is growing rapidly owing to new accelerators dedicated to studying the isotopes far from their stable isobars [2].

Investigation of nuclear properties and the law of governing medical the structure of nuclei is an active and productive area of physical research in its own right,and practical application,such as smoke detectors,cardiac pacemakers,and medical imaging devices have become common.

Any nuclei with finite life time are produced by nuclear reactions and/or nuclear decays,though the number of stable nuclei is limited to less than 300 if we call those nuclei whose lifetime is longer than or nearly equal to the age of universe,i.e about 13.8×10^9 years as stable nuclei. Also,all the excited states of nuclei eventually decay into other nuclei via alpha or beta decay or fission,or make transition to lower energy levels of the same nucleus by emitting gamma rays.The decay called cluster decay or heavy particle decay or cluster radioactivity . Further,three different modes of radioactivity were observed emitting α-particles, β-particle and γ-rays[3].

It is well known that alpha-particles are Helium nuclei, beta-particles are either electrons or positrons and gamma-rays are high-energy electromagnetic radiations. Scattering of alpha-particles with matter revealed the existence of nucleus inside the atom [4].

This process of bombarding a target nucleus by fast moving projectiles and the subsequent interaction between the two, which alters the composition, energy, etc. of the target nucleus is known as **nuclear reaction**. This is also known as **transmutation** of one element into another. Suppose a target nucleus X is bombarded by particle a. During this process a new nucleus Y is formed and a particle (or gamma-ray) b is emitted, then this nuclear reaction is written as:

$$a + X = Y + b$$

This reaction is also denoted as:

$$X(a, b)Y$$

For example, consider the following reaction:

$$^{4}\text{He} + {}^{9}\text{Be} \rightarrow {}^{12}\text{C} + {}^{1}\text{n}$$

Radiation from radioisotope plays a very important role in all fields, useful in our life such as soil and earth science, radioactive dating, environment, archeology, agriculture, biochemical analysis, radiotherapy and cancer treatment, medical diagnosis, nuclear medicine, biological sciences, sterilization of medical products, nondestructive elemental analysis and testing of materials, oceanography, pharmaceutical, radioisotope power systems for space applications and many more[5].

Nowadays, many different stable and radioactive isotopes, each with unique physical and chemical properties, play significant roles in technological applications of importance to our modern society and are substantial to scientific research. One of the most common applications is the use of the radioisotope in medicine.

Medical radioisotopes are used to label some special chemical compounds to form Radio pharmaceuticals. Radio pharmaceuticals are used extensively in the field of nuclear medicine in three main branches.

The largest and the most common type involve **Diagnostic** procedures in which a radionuclide in a chemically suitable form is administered to the patient, and the distribution of the radioactivity in the body is determined by an external radiation detector. The results are in the form of image of the involved organ, which provides information about the functioning of person's specific organs via emission tomography [6].

The second branch of nuclear medicine deals with radionuclide techniques that are used for the **Analysis** of concentration of hormones, antibodies, drugs and other important substances in samples of blood or tissues [7].

The third branch is **Radiation therapy**, which is the ultimate aim of all diagnostic investigations.Here the tissues or organs are treated with radiation and restored to the normal functions in the human body[8].

1.2 Objective of the Study

1.2.1 General Objective

- To evaluate the excitation function of Deuteron induced reactions for the production of medically important radionuclide.

1.2.2 Specific Objective

- To identify the reaction taking place in the production of selected medically essential radionuclide.
- To calculate the cross sections of Deuteron induced reactions for production of ^{125}I,^{62}Zn, ^{15}O and ^{103}Pd at different energy level.
- To figured out the discrepancy between the theoretical calculated nuclear reaction cross sections with ENDF data file cross-sections.

1.3 Statement of the Problem

- This research work emphasize on theoretical deuteron induced computation of excitation function of the selected radioisotope and try to figured out the discrepancy with the experimental excitation function data file.

1.4 Significance of the Study

This research work:

- Plays it's role on enhancing on the production of medically important radioisotope.
- Gives awareness about theoretical computation of excitation function of radioisotopes and can be used as a guideline for the coming generation.

CHAPTER 2

REVIEW OF RELATED LITERATURE

2.1 Radio pharmaceuticals

Nuclear medicine is returning to its origin by studying more and more metabolic signals using new positron or single-photon-emitting radio pharmaceuticals. The history of nuclear medicine over the past 50 years highlights the strong link between investments in chemistry and the development of radionuclides and radio labeled compounds. The development of radio pharmaceuticals began in the mid twentieth century, where as technetium/molybdenum generator was primarily recognized as source of diagnostic radioactivity by FAD in 1970 [9].

Radioactive substances containing single or more radionuclide suitable for administration to humans for diagnostic purposes or for radiation therapy are known as **Radio-pharmaceuticals** [10].

Radio pharmaceuticals are radioactive compounds which have a bound radionuclide in their structure, whose purpose is directing the radionuclide to a location to be treated or to obtain images. Radio pharmaceuticals generally consist of two components, a radioactive element (radionuclide), that permits external scan, linked to a nonradioactive element, and a biologically active molecule, drug or cell (red and white blood cells labeled with a radionuclide, for example) that acts as a carrier or ligand, responsible for conducting the radionuclide to a specific organ [11].

The distribution of the radio pharmaceutical within the body is determined by the physio chemical properties of the drug, the stability of the radio-label, the purity of the radio pharmaceutical preparation, the pathophysiologic state of the patient, and the presence or absence of interfering drugs.

Dynamic and static images of the distribution of the radio pharmaceutical within the body can be obtained using a gamma-camera or another suitable instrument appropriate for the radio pharmaceutical being imaged-for example, positron emitting radio pharmaceutical.After administration of the radio pharmaceutical, radioactivity in specified sites of accumulation or in biologic samples can be measured for non imaging procedures. High-dose, non penetrating radiation in localized sites of accumulation of the radio pharmaceutical can be useful for therapeutic procedures. [12].

The selection criteria of important radioisotope in nuclear medicine are nuclear decay

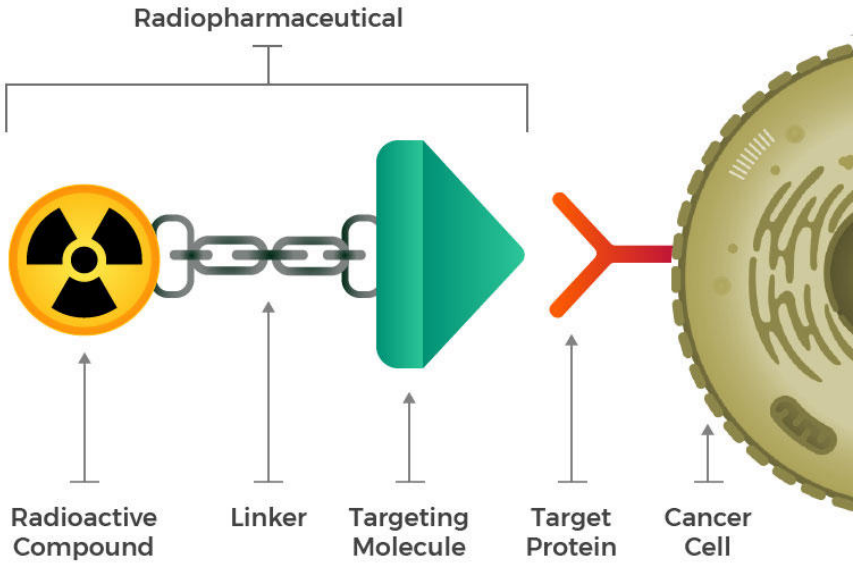


Figure 2.1: Radiopharmaceuticals-diagram.

properties, half-life, chemical properties and ease of large scale production. The application of radioactive isotopes in nuclear medicine depends on the types of emitted ionizing radiation.The longer range, more penetrating radiation is used for imaging purposes since it can be detected outside the patient's body.While,the shorter range radiation is therapeutically used to deposit a maximum amount of energy within a specified body region. Some characteristics are necessary for considering radio-pharmaceuticals clinically useful for imaging:

- The decay of the radionuclide should be in specific ranges of energy emissions (511 keV for positron emission tomography and 100-200 keV for gamma cameras) and in sufficient quantity for tomography detection.
- It should not contain particulate radiation (beta emissions), because it increases the radiation dose in patients.
- The half-life should be for a few hours only.
- The radionuclide should not be contaminated by other radionuclide of the same element nor even its stable radionuclide (carrier-free).
- They should have specific activity, and the highest specific activity comes from carrier-free radionuclide.
- The radio pharmaceutical should not have toxicity and does not manifest physiological effects.
- The radio pharmaceutical should be available for instant usage and easy to compound.
- The radio pharmaceutical should reach the target organ quickly and accurately, according to its intended application.

Diagnostic radio pharmaceutical have no pharmacological effects and their administration is not associated with relevant clinical side effects. However it carries the inherent risk of exposure to radiation and possible contamination during radio pharmaceutical formulation, since most radio pharmaceuticals are administered intravenously.

Unlike drugs given for therapeutic purposes, radio pharmaceuticals rarely cause adverse reactions. The explanation for the safety of radio pharmaceuticals lies not only in the very small mass of drug injected or ingested, usually in the micro gram range, but also because radio pharmaceuticals are typically administered only once or a very limited number of times to any given patient. The use of a radio pharmaceutical is not based upon its ability to produce a pharmacological effect, but rather on differences in the distribution and pharmacokinetics of the agent between normal and abnormal physiological processes.

In fact, the production of pharmacological or physiological effects by a radio pharmaceutical is undesirable since the agent should not modify the parameter it is attempting to measure. Unusual ("idiosyncratic") sensitivity to a pharmacologie effect is virtually never seen [13]. Naturally occurring radionuclide are generally not suitable for diagnostic and therapeutic procedures due to their typically long half-lives or less than ideal physical or chemical characteristics; therefore appropriate radionuclide need to be produced artificially.

2.2 Radionuclide production

More than 150 different radioisotopes (RIS) are playing an important role in medical, industrial, research, and commercial applications, such as food processing, agriculture, and structural safety. The medical use of RIS for diagnostic imaging studies and therapeutic applications accounts for the majority of applications.

Radio pharmaceuticals (RPs) are molecular tools that nuclear medicine (NM) routinely employs for the diagnosis and treatment of diseases. The success of NM is deeply rooted in the close collaboration between nuclear physics, chemistry, biology, and pharmacology. [14].

Radioisotopes are isotopes that are unstable, or radioactive, and give off radiation spontaneously. Many radioisotopes are produced by bombarding suitable targets with neutrons now readily available inside atomic reactors. Some of them, however, are more satisfactorily created by the action of protons, deuteron, or other subatomic particles that have been given high velocities in a cyclotron or similar accelerator.

Many isotope separation methods that have been developed, two(electromagnetic and thermal diffusion) are used commonly to produce small quantities of many isotopes for research purposes, and two others (the GS chemical-exchange process for hydrogen, gaseous diffusion for uranium) are used on an industrial scale. The large-scale use of gas centrifuges for uranium is imminent, and laser separation methods appear promising for uranium, deuterium, and expanded-scale production of research materials.In addition to the applications of ^{235}U and deuterium in nuclear energy. separated isotopes serve as chemical tracers and as targets or beam particles in radioisotope production and nuclear research[15].

The amount of radioisotope produced depends on three key factors:

- The quantity of bombarding particles
- The quantity of target nuclei
- The reaction's cross section

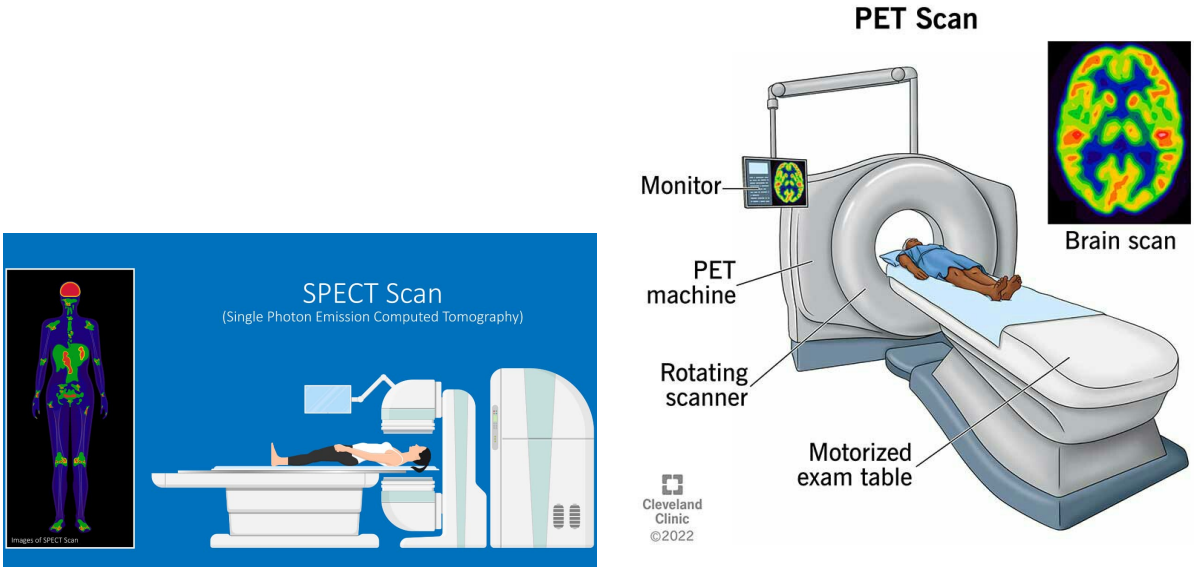
The length of bombardment is also important since the production of short lived nuclei can reach saturation rather quickly. In order to optimize the production of a particular radionuclide the following production considerations must be taken into account:

- the threshold energy for the desired reaction
- the energy where the maximum yield occurs
- the chemical form of the target nucleus
- the physical form of the target nucleus
- the chemical form of the desired product
- the physical form of the desired product, and
- the ease of separation of product from the target [16].

RIS (Radioisotopes) typically used for nuclear medicine are produced in reactors or accelerators. In reactors, neutron-rich RIS are produced via the fission reaction of ^{235}U, or the thermal neutron capture reaction by a sample nucleus. Since the produced RIS are mostly neutron-rich nuclei, they decay by emitting γ-rays and/or β^--particle.

Radio pharmaceuticals containing β^--particle emitting radionuclide are used to kill targeted cancer cells in radio immuno therapy (RIT), and those containing γ-ray emitting radionuclide are used to diagnose the dynamics of a medicine in the living body via single-photon emission computed tomography (SPECT) in nuclear medicine imaging (NM).

In accelerators, a wide range of RIS including many proton-rich light RIS, such as ^{18}F and ^{11}C,are produced using mostly proton beams with their energies being between 10 and 200 MeV . These RIS decay mostly by emitting β^+-particle or α-particle. Radio pharmaceuticals containing β^+-particle and α-particle emitting radionuclide are used in NM and RIT, respectively [17].



(a) SPECT-Scanner **(b)** PET-Scanner

Figure 2.2: Diagnostic imaging devices.

2.2.1 Nuclear fusion

Nuclear fusion is the process by which two light atomic nuclei combine to form a single heavier one while releasing massive amounts of energy. Fusion reactions take place in a state of matter called plasma hot, charged gas made of positive ions and free moving electrons that has unique properties distinct from solids, liquids and gases [18].

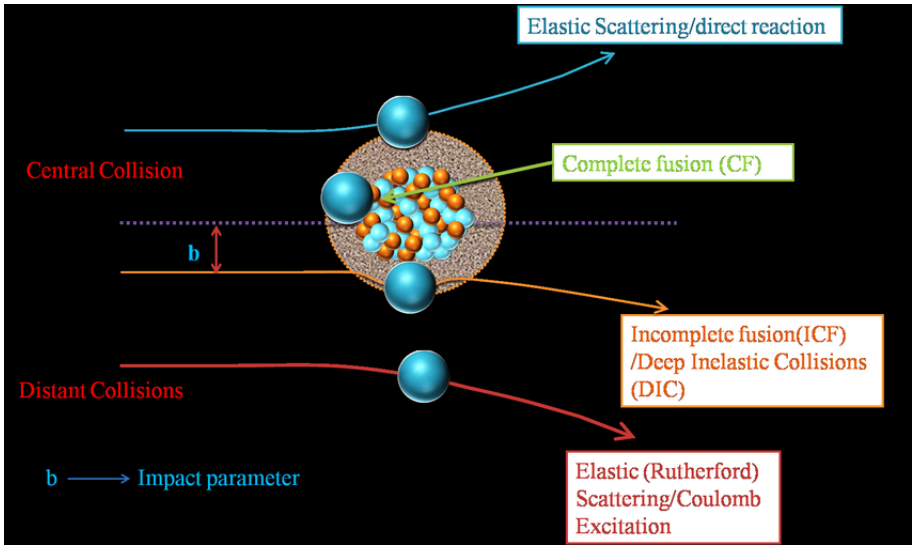


Figure 2.3: Pictorial representation possibilities of interactions of heavy ion with nucleus, showing various projectile trajectories.

Complete fusion

Complete Fusion reactions is the process in which the projectile completely fuses with the target, which leads to the formation of excited composite system , and then it de-excites by particle and/or gamma-ray emission.

The occurrence of heavy fissile nuclei produced in fusion-evaporation reactions strongly depends on both components of fission barriers for nuclei in the de-excitation cascade of a compound nucleus (CN) formed in complete fusion; namely the macroscopic part reduces with the increase in an angular momentum L, whereas the shell effect fades out in the nuclear level density with the increase in an excitation energy [19].

If the heavy ion is having sufficient energy to over come the potential barrier the chance of its complete fusion increases. Also the complete fusion depends up on the impact parameter when $b < R_{ion} + R_{nuc}$ and energy is a round or more than coulomb barrier, the complete fusion of projectile may take place and the formation of compound nucleus is possible. This complete fusion reaction of heavy ion will be more at high energy as compare with incomplete fusion.

There are some of the important features of CF reaction that may explained by considering the behavior of the nuclear reaction potential and assuming that CF between the heavy ions occurs for all those partial waves which permits the two ions to move close to each other so that they get trapped in a pocket. If these condition are not fulfilled, the two ions are reflected back and do not fuse at all.

- The projectile and target should have maximum mass overlap for fusion to occur.
- The excitation function (variation of cross-section with the incident projectile energy) of the evaporation residues, formed through the CF of different pairs of interacting ion, resulting in to the same compound nucleus may different considerably
- The projectile energy must be sufficient enough to overcome the fusion barrier of the projectile-target system[20], [21], [22].

  Fusion Barrier:

$$V_{CB} = \frac{Z_P Z_T}{A_p^{1/3} + A_T^{1/3}} \tag{2.1}$$

Incomplete fusion

In the case of Incomplete Fusion reactions mechanism, the projectile breaks into two fragments, of which one will fuse with the target to form an excited composite system, which may decay via emission of light-particles and/or gamma-rays, while the other fragment moves forward as spectator with same velocity as that of the projectile carrying a large part of the angular momentum and kinetic energy of the projectile. For larger impact parameter that means $b > R_{nuc} + R_{ion}$ the incident heavy ion will have interaction of the type of Elastic Scattering and coulomb excitation of nucleus which no nuclear force are involved. The nucleus is de-excited by the emission of photons or low energy γ- ray. As the impact parameter decreases that means $b \approx R_{ion} + R_{nuc}$ it is grazing incidence[20], [21], [22].

The common features of these ICF reactions are:

- They are observed in the case of low-Z projectile ($Z \geq 10$);

- The recoil-range distributions (RRD) of the heavy residues show a low-range component suggesting incomplete momentum transfer; and
- The outgoing particles have forward peaked angular distribution and energy spectrum peaked at beam velocity. These are also called as massive transfer reactions [23].

2.2.2 Nuclear fission

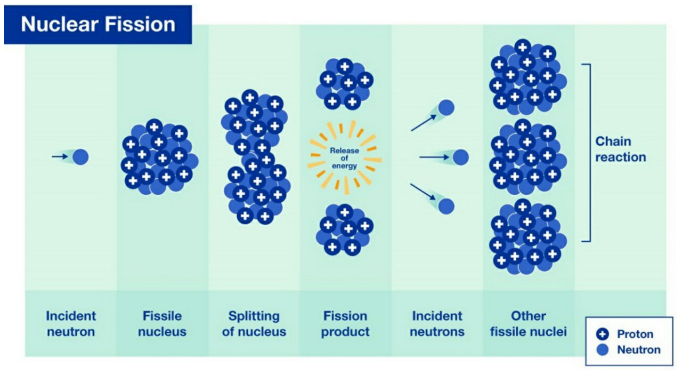


Figure 2.4: Nuclear Fission.

Nuclear fission is a complex process, in which a heavy nucleus evolves from a compact shape to a configuration in which two or more fragments are produced, and is accompanied by emission of prompt neutrons and gamma rays (and, eventually, electrons and anti neutrinos). Most of the energy is released in form of kinetic energy of the fragments, while prompt neutrons emitted before beta decays play the main role in applications like energy production [24].

A nucleus that undergoes fission has to change its shape from a round-shaped or somewhat deformed ground state to some elongated dumbbell-like configuration, which finally divides into two fragments. Such a large-scale collective motion cannot be observed in other processes at low nuclear temperature [25].

The neutron is used to splitting the atom of a large nucleus to create an unstable nucleus in a nuclear reactor. While this can occur spontaneously in unstable nuclei in the nuclear reactor we add energy by way of a neutron. Given that a neutron has no charge, they can penetrate a target nucleus without being accelerated to high energies.

The common and fissionable reaction of nuclide with high atomic number is the fission of uranium-235 (^{235}U) by neutrons in a nuclear reactor. For instance, iodine-131 (^{131}I), molybdenum-99 (^{99}Mo) and xenon-133 (^{133}Xe) can be produced by this manner.

2.2.3 Neutron Bombardment

Radionuclide are produced by bombarding target materials with neutrons in nuclear reactors. The desired nuclear reaction will be influenced by the energy of the incident particle and by the isotopic composition and purity of the target material. Reactor-produced radionuclide important to nuclear medicine.

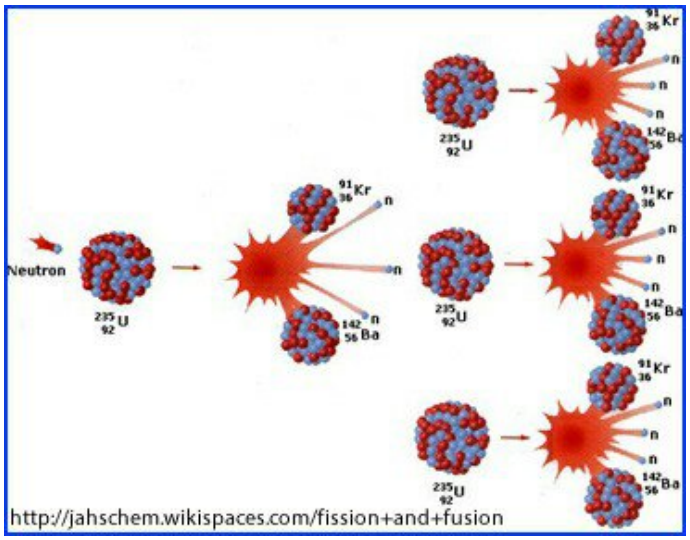


Figure 2.5: Neutron bombardment.

There are three general reaction types used: neutron radiative capture (n,γ); neutron capture followed by particle emission, e.g, (n,α), (n,p), and and fission (n,f).The most widely used route is the (n,γ) reaction with thermal neutrons. The advantage of this production process is its simplicity and high yield[26].

2.2.4 Cyclotron

Cyclotrons are used to accelerate charged particles such as protons (p), deuteron (d), triton (t) and alpha (α) particles to high velocities to penetrate the orbital electrons of the target atom and interact with the nucleus[27].

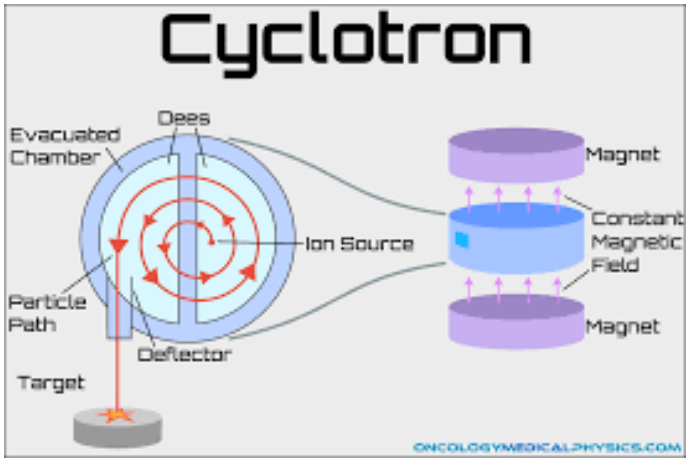


Figure 2.6: cyclotron.

Cyclotrons are a circular charged particle accelerator under high vacuum that uses a magnetic field to confine particles to a spiral flight path in a vacuum chamber. At last particle beam with adequate energy allow transformation at the atomic level and deviated to hit a target. The radionuclide produced by cyclotrons typically have low neutron counts and decay mostly by Electron Capture or β^+ particle emission.

Radionuclide produced with a cyclotron, and their corresponding radio pharmaceuticals,

are extremely valuable in basic medical research, disease diagnosis and radiotherapy treatment.Radionuclide production technology at cyclotrons has been well developed, especially for short-lived organic positron emitters,commonly used SPECT radionuclide,and a few therapeutic radioisotopes, They are especially suitable for diagnostic studies[28].

2.2.5 Generator

Generator systems are used to produce high specific activities of reactor produced isotopes, by indirect production schemes and, in some cases, by direct (n,γ) activation. Generators produce the most commonly used radionuclide in nuclear medicine, technetium-99m (^{99m}Tc). The radionuclide generator sees the decay of a long half-life parent radionuclide to a short half-life daughter radionuclide. The daughter is the radionuclide used in nuclear medicine[27].

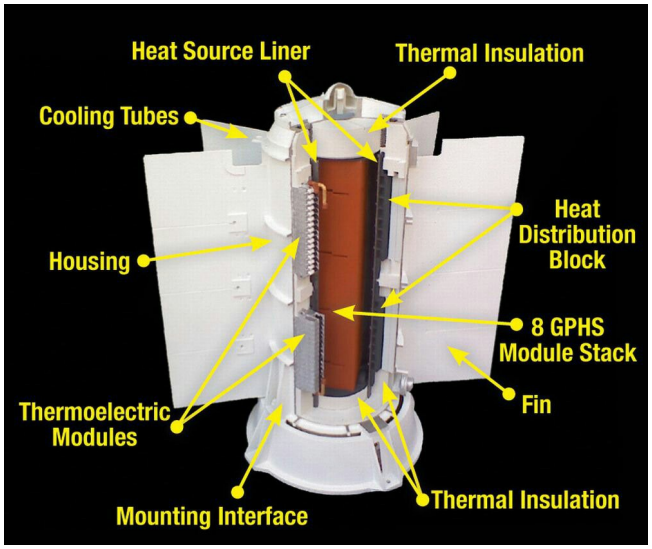


Figure 2.7: Generator.

2.3 Reaction mechanisms

In a projectile target nucleus interaction either of two things may happen, the projectile may simply be deflected by the target nucleus potential and change its direction without any change in the center of mass energy, This shape is **Elastic scattering**. On the other hand, the projectile may interact with target particle, lose energy to it and thus be removed from the entrance channel to be absorbed by the target nucleus. After the absorption nuclear reaction may occur by any of three processes: **Direct reaction mechanism, Compound nuclear emission** or by **Pre-equilibrium emissions**[29].

2.3.1 Direct reaction

Nuclear reaction may take place only with certain parts of the target nucleus being the rest undisturbed. A direct reaction takes place when the projectile interacts primarily with the nucleons in the surface of the target nucleus

The interaction is with one or two nucleons. Energy and momentum transfer is very small and the transfer is to only few nucleons and emission of the particle most probably is in direction of motion of the projectile,the reaction which take place with out the formation of compound nucleus are called direct reaction.
These reactions occur on very short time scales ($10^{-22}se \rightarrow 10^{-21}se$, which is roughly equal to the time it takes the incident particle to traverse the target nuclei) [20], [29],[30].

2.3.2 The compound Nucleus reaction

At the other extreme we have the compound nuclear reactions, these reactions are important at comparatively low incident energies. In this case there is no emission after a single interaction. Instead both the projectile and the excited nucleon (or cluster) remain inside the nucleus and undergo further interactions inside the nuclear matter.

Through successive interactions the energy and momentum brought in by the projectile are diffused through the nucleus and eventually transferred to the composite nucleus as a whole. As more and more degrees of freedom are excited following each interaction throughout the energy-momentum sharing process, the nuclear state inevitably grows more complicated.

These reactions occur on relatively long time scales ($10^{-18}se \rightarrow 10^{-16}se$) . After these many interactions, if the energy is sufficient, a nucleon can be ejected from the nucleus. Once equilibrium is reached,the compound nucleus retains no memory of its mode of formation and the decay modes of the compound nucleus are the very general ones. When the ejected particles emerge from the reaction, they have relatively low energies. In contrast, the remaining nucleus is left with a high degree of excitation, in a region where there is a large density of nuclear energy levels. As a result, the spectrum or distribution of energies for the ejectile particles is continuous, rather than exhibiting discrete, well-defined peaks[20], [29],[31].

2.3.3 Pre-equilibrium reaction

If the projectile interacts with a limited number say 2 to 5 nucleons, before the striking projectile and or the ejectiles come out, this is a case of **pre-compound reaction mechanism**.Pre-equilibrium reaction is neither direct nor compound nucleus reaction.

In this type of reactions particles are emitted after the first stage of a nuclear interaction(direct reaction)but long before the attainment of statistical equilibrium (compound nucleus formation).Their time scale $(10^{-22}se < t < 10^{-18}se)$ is intermediate between the very fast direct reactions and the relatively slow compound nucleus formation [20], [29].

2.4 Clinical application of Radionuclide

Radionuclide therapy uses radioactive isotopes labelled with specific targeting agents that aim to deliver the irradiation of the isotope to the tumor, while sparing normal tissues. Another important principle is its so-called **cross-fire action**, whereby, owing

to the larger reach of the radiation in relation to the cell diameter, a tumor cell receives lethal hits also from isotopes in the neighborhood that are not directly associated with this cell.The treatment is therefore less hampered by inhomogeneous distribution and metabolism than for example chemo-or immunotherapy [32].

When selecting a radionuclide for clinical application, the physical and biochemical characteristics must be considered. Physical characteristics include physical half-life, type of emissions, energy of the emissions, daughter products, method of production, and radionuclidic purity.

Biochemical characteristics include tissue targeting, retention of radioactivity in the tumor, in vivo stability, and toxicity . For radiotherapy, it is desirable to have a high linear energy transfer (LET), where there is a high ionization energy deposited per unit length of travel.

Radionuclide with a high LET deposit radioactive emission energy within a small range of tissue, thereby sparing surrounding healthy tissue and keeping the radioactive dose within, as much as possible, the patient's organ to be treated [33].

2.4.1 Alpha particle emitter

The investigation of the therapeutic potential of alpha-particle emitters has focused mainly on five radionuclide: Astatine-211 (^{211}At),Bismuth-212 (^{212}Bi),Bismuth-213 (^{213}Bi),Radium-223 (^{223}Ra),and Actinium-225 (^{225}Ac) [34].

Table 2.1: some examples of α-emitting radionuclide

α **emitting Radionuclide**	**Beam of Energy range in Mev**	**Half-life** ($t_{1/2}$)	**Clinical application**
^{211}At (Astatine-211)	28-29.5	7.2 hr	for treatment of ovarian cancer [35],[36]
^{225}Ac (Actinium-225)	5-8	10 days	brain tumors,neuroendocrine tumors, melanoma and prostate cancer [37]
^{212}Bi (Bismuth-212)	6.1	60.6 Min	Melanoma,leukemia, neuroendocrine tumors...etc[38]
^{223}Ra (Radium-223)	5-7	11.4 days	used as radium chloride for prostate meta states cancer[39]
^{227}Th (Thorium-227)	6.0	18.7 days	Breast cancer, ovarian cancer,acute myeloid leukemia and renal cell carcinoma[39]

The advantage of using alpha particles is their short range (50-90μm), high linear energy transfer (LET) and independence from dose rate and oxygen effects. A major disadvantage is the difficulty in measuring and/or modeling the spatial and temporal distribution of the source activity. Moreover, the dosimetry of alpha-particle emitters is a challenge because the dimensions of sub cellular targets (e.g. cell nuclei) are of the same order of magnitude as the range of the particles[40].

Alpha particles that are emitted by radionuclide are suitable for some therapeutic applications and alpha-emitting radioisotopes are less effective to large tumors, due its highest linear energy transfer (LET) ($\approx$ 80 keV/μm) and smallest particle path length (50-100μm).

The high potency and short range can also lead to toxicity. To anticipate or reduce toxicity while optimizing efficacy, early phase α RPT trials should be designed with an understanding of the dosimetry and radiobiology of the α RPT under investigation [41].

2.4.2 Beta particle emitter

The process of electron capture and the emission of either electrons (β^-) or positrons (β^+) are viewed as smaller charged particles known as **Beta** particles. The emission of high speed electrons(β^-) and anti neutrinos with kinetic energies ranging up to the maximum value of the decay energy (E_{max}) resulted from β^-decay of neutron-rich radionuclide.

This electron requires a few millimeters of aluminum to absorb them and travels many hundred times in air than alpha-particles. However, Positrons are emitted with a constant energy distribution; they lose most of their kinetic energy as well as exist for only short period of time and combine with an electron. This extinction results two energy of 511 KeV photons emitted in opposite direction[42].

Table 2.2: some examples of β-emitting radionuclide

β-emitting radionuclide	**Beam of energy range in Mev**	**Half-life ($t_{1/2}$)**	**Clinical application**
^{32}P (Phosphorus-32)	1.71	14.2 days	for the myeloid bone cancer associated with palliative therapy [43]
^{89}Sr (Strondium-89)	1.5	50.5 days	for the treatment of metastatic bone cancer[44]
^{67}Cu (Copper-67)	0.4	61.9 Hrs	for the treatment of radio immunotherapy [45]
^{90}Y (Yitrium-90)	2.3	64 Hrs	treat patients with unresectable liver cancer(primary and secondary)[46]
^{131}I (Iodine-131)	0.61	8.05 days	used for the treatment of malignant diseases such as gliomas, pheochromocytoma and carcinoids, Thyroid cancer and non-malignant thyroid disorder [47]
^{186}Re (Rhenium-189)	1.1	3.7 days	for pain relief of bone cancer [48]

In another case, proton-rich nuclide can be stable by electron capture.Beta emitters are the most common radionuclide in radio-medicine because; of wide spectrum energy ranges and the most selected radionuclide suitable for radiotherapy.

In the case of large tumor treatment high energy beta particles are preferable.The needed

and desirable dose beta particles would be deposited in tissues around the tumor for small volume tumors [49].

Beta and gamma emitting particles are simultaneously used for imaging, pure β emitters provide a high local dose,which makes them more ideal for therapy. However, the overall dose of the patients increases without any therapeutic benefit [50].

2.4.3 Auger electron and Coster-Kronig electron emitter

Auger electron is named in 1925 after the discovered by French physicist Pierre Auger.It is formed when an electron captured from a higher energy level fills the vacancy created in an inner shell. However,most of the excess energy is emitted as X-ray energy and some are excited as kinetic energy given to another electron.

Auger electrons (AEs) are very low energy electrons that are emitted by radionuclide that decay by electron capture(e.g.^{111}In,^{67}Ga,^{99m}Tc, ,^{125}I, ^{123}I,^{90}Nb,^{201}Tl,) [51]

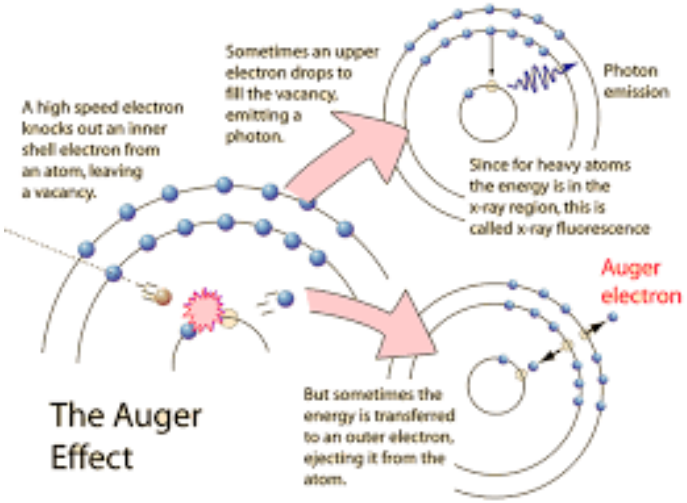


Figure 2.8: The Auger effect.

This energy is deposited over nanometer-micrometer distances, resulting in high linear energy transfer (LET) that is potent for causing lethal damage in cancer cells.Thus,AE-emitting radiotherapeutic agents have great potential for treatment of cancer [52].

This extremely short range yields high linear energy transfer (LET), which makes AEs attractive for radiation treatment of cancer, especially if they are emitted in close proximity to cell sensitive targets such as DNA and the cell membrane. Auger electrons have high linear energy transfer (4-26 keV/μm) that requires radionuclide to cross the cell membrane and reach the nucleus because the limited path length of 2-500 nm restricts their efficacy to single cells [49].

In addition, radiation emitted during the nuclear decay can be exploited for imaging purposes either with SPECT (in the case of γ-rays in the energy range of 70-360 keV or Bremsstrahlung imaging for pure β^--emitters) or PET (in the case of annihilation

photons), thus making Auger electron-emitting radionuclide ideal as theranostic agents [53].

Table 2.3: some examples of Auger electron-emitting radionuclide

Auger electron-emitting radionuclide	**Beam of energy range in Mev**	**Half-life ($t_{1/2}$)**	**Clinical application**
^{67}Ga (Gallium-67)	93-393.5	3,26 days	used for imaging of lymphoma tumors[54]
^{99m}Tc (Technetium-67)	140	6 Hrs	take imaging for the patient with bone metastases[55]
^{111}In (Indium-111)	171-245	2.8 days	used to scan leukocyte[55]
^{123}I (Iodine-123)	159	13.2 Hrs	used for thyroid imaging[56]
^{125}I (Iodine-125)	27	59.4 days	Treat prostate cancer and brain tumor[57]

2.5 Modes of decay for radioactive substance

Nucleons are bound together to form the nucleus by the strong nuclear force,to bind the nucleons into a stable nucleus,a delicate equilibrium between the number of protons and the number of neutrons must exist.

For light (low A) nuclear species, a stable nucleus is formed by an equal number of protons and neutrons ($Z = N$). Above the nucleon number $A \approx 40$, more neutrons than protons must constitute the nucleus to form a stable configuration in order to overcome the Coulomb repulsion among the charged protons.

If the optimal equilibrium between protons and neutrons does not exist, the nucleus is unstable (radioactive) and decays with a specific decay constant λ into a more stable configuration that may also be unstable and decay further, forming a decay chain that eventually ends with a stable nuclide.

General aspects of spontaneous radioactive decay may be discussed using the formals based on the definitions of activity "A" and decay constant "λ" without regard for the actual microscopic processes that underlie the radioactive disintegrations[58].

The time rate of decay of a radioactive sample containing N_0 , atoms at $t = 0$ is given by:

$$-\frac{dN}{dt} = \lambda N \tag{2.2}$$

integration from $t = 0$ to t yields:

$$N = N_0 e^{-\lambda t} \tag{2.3}$$

The decay constant "λ" is a measure of the rate at which the radioactive nuclei spontaneously decay over time. This, combined with the number of radioactive nuclei N at a given time t, determines the radioactive decay behavior:

$$A = A_0 e^{-\lambda t} \tag{2.4}$$

Where; "A" is the activity remaining after time of decay, t and A_0 is the original activity. Formerly, curie (Ci) used as the basic unit of radioactivity [57].

$$1Ci = 3.7 \times 10^{10} dps \tag{2.5}$$

Half -life is the time in which the radioactivity decreases to one-half (1/2) its original value.

$$t_{1/2} = \frac{0.693}{\lambda} \tag{2.6}$$

The decay constant (λ) is given by

$$\lambda = \frac{ln2}{t_{1/2}} \tag{2.7}$$

The specific activity of a sample is defined by the activity per unit mass.The specific activity **S** is determined by T (time) and atomic mass M. Because the number of atoms per gram is $6.022 \times 10^{23}/M$.

$$S = 4.17 \times 10^{23}/MT \tag{2.8}$$

The unit of S is Bq g^{-1} if T(time) is in seconds [59].

The choice of suitable radionuclide for therapeutics is depend on the effective half-life which includes both physical half-life (T_p) and biological half-life (T_b) within the patient's body or organs. Effective half-life (T_e) is explained in the medical internal radiation dosimetry(MIRD) calculation method, which is summarized as [60];

$$T_e = \frac{T_p T_b}{T_p + T_b} \tag{2.9}$$

where:

- T_e is Effective half-life

- T_p is physical half-life
- T_b is biological half-life

2.6 Interaction of radiation with matter

Radiation originally meant α**-particle,** β**-particle**, and γ**-rays** emitted from natural radioactive isotopes. At present, elementary particles, nuclei, electrons, and photons, moving with speeds comparable to or higher than the rays from radioactive isotopes, are called **Radiation**.

The reason for using the term rays is that the path of particles has direction. When radiation passes through matter, it has the capability of direct or indirect ionization of atoms and molecules. Hence we use the term ionizing radiation [59].

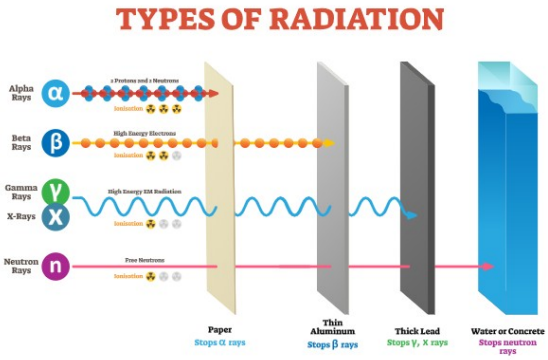


Figure 2.9: Types of Radiation.

For the treatment of bulky tumor radionuclide that emit energetic α-particle or β-particles are preferred. However, radionuclide that emit Auger electrons are thought to be more advantageous because of their high-level cytotoxicity and short-range biological effectiveness, for the treatment of small clusters of cancer cells or small tumor deposits [61].

The nature of radiation and the interaction between the molecular systems influences the interaction of radiation with matter. The interaction between magnetic fields of the radiation and the oscillating electric with the electric or magnetic dipole moment of an atom or molecule affects the mechanism of interaction between electromagnetic radiation and matter.

The electrostatic interaction between its electric dipole moment and the oscillating electric field of the electromagnet is depending on a molecular system force. The existence of a permanent electric or magnetic dipole or the instantaneous creation of an electric dipole due to internal motions is essential for the interaction between atoms or molecules and the electromagnetic radiation [62].

The major difference between these types of radiation is in terms of the relative biological effectiveness (RRE) of the radiation: the effectiveness with which exposure to the radiation affects on the specific endpoints under consideration. with these biological endpoints has shown that the effects of exposure to heavy particles are qualitatively similar to the effects of exposure to low LET types of radiation. The major difference seems to be that high LET heavy particles are generally more effective in producing alterations in these biological end points than is exposure to other types of radiation [63].

2.7 Types of Radiation

Radiation is the transfer of energy through particles or electromagnetic waves and it may be ionizing or non-ionizing. Radioactive decay processes shows that they are divided into six categories, consisting of three main categories of importance to medical use of radionuclide and three categories of less importance.

The main categories are [64]:

- alpha (α) decay,
- beta (β) decay encompassing three related decay processes (beta minus, beta plus and electron capture) and
- gamma (γ) decay encompassing two competing decay processes (pure γ decay and internal conversion)

The three less important radioactive decay categories are:

- spontaneous fission
- proton emission decay and
- neutron emission decay

2.7.1 Alpha decay

In α decay process, a radioactive parent nucleus P decays into a more stable daughter nucleus D by ejecting an energetic particle. Since the α particle is a ^{4}He nucleus ($^4_2\mathrm{He}^{2+}$), the parent's atomic number Z decreases by two and its atomic mass number A decreases by four:

$$^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P} \rightarrow {}^{\mathrm{A}-4}_{\mathrm{Z}-2}\mathrm{D} + {}^{4}_{2}\mathrm{He}^{2+} = {}^{\mathrm{A}-4}_{\mathrm{Z}-2}\mathrm{D} + \alpha \tag{2.10}$$

Naturally occurring α particles have kinetic energies between 4 and 9 MeV ; their range in air is between 1 and 10 cm, and their range in tissue is between 10 and 100 μm [65].

Typical examples of α decay are the decay of ^{226}Ra with a half-life of 1602 yrs into ^{222}Rn which is also radioactive and decays with a half-life of 3.82 d into ^{218}Po:

$$^{226}_{86}\mathrm{Ra} \rightarrow {}^{222}_{85}\mathrm{Rn} + \alpha, T_{1/2} = 1602yr \tag{2.11}$$

$$^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + \alpha, T_{1/2} = 3.86d \tag{2.12}$$

2.7.2 Beta decay

Beta Minus decay

In beta minus (β^-) decay, a neutron-rich parent nucleus P transforms a neutron into a proton and ejects an electron e^- and an electronic anti neutrino v^-e .Thus, in β^- decay, the atomic number of the daughter increases by one, i.e. $Z_D = Z_P + 1$, the atomic mass number remains constant, i.e. $A_D = A_P$, and the general relationship for β decay is given as:

$$^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P} \rightarrow {}_{\mathrm{Z+1}}{}^{\mathrm{A}}D + e^- + v^-e \tag{2.13}$$

A typical example of β^- decay is the decay of ^{60}Co with a half-life of 5.26 yrs into an excited state of ^{60}Ni ($^{60}_{28}$Ni*) progress to the ground state of ^{60}Ni instantaneously (within $10^{-12}se$) through emission of γ-decay [66]:

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^- + v^-e, T_{1/2} = 5.26yr \tag{2.14}$$

Beta Plus decay

In beta plus (β^+) decay, a proton-rich parent nucleus P transforms a proton into a neutron and ejects a positron e^+ and an electronic neutrino v_e. Thus, in β^+ decay, the atomic number of the daughter decreases by one, i.e. $Z_D = Z_P - 1$, the atomic mass number, just as in β decay, remains constant, i.e. $A_D = A_P$, and the general relationship for β^+ decay is written as:

$$^{\mathrm{A}}_{\mathrm{Z}}\mathrm{P} \rightarrow {}_{\mathrm{Z-1}}{}^{\mathrm{A}}\mathrm{D} + e^+ + v_e \tag{2.15}$$

Radionuclide undergoing β^+ decay are often called positron emitters and are used in medicine for functional imaging with the special imaging technique PET. The most common tracer for PET studies is fluorodeoxyglucose (FDG) labelled with ^{18}F which serves as a good example of β^+ decay [59]:

$$^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{9}\mathrm{O} + e^+ + v_e, T_{1/2} = 110min \tag{2.16}$$

Gamma decay and Internal conversion

Alpha decay as well as the three β decay modes (β^- , β^+ and electron capture) may produce a daughter nucleus in an excited state without expending the full amount of the decay energy available. The daughter nucleus will then reach its ground state, either instantaneously or with some time delay (isomeric metastable state), through one of the following two processes:

- By emitting the excitation energy in the form of one or more γ photons in a decay process referred to as γ decay.
- By transferring the excitation energy to one of its associated atomic orbital electrons (usually a K shell electron) in a process called **Internal conversion**. The vacancy left behind by the ejected orbital electron is filled by a transition from a higher atomic shell, resulting in characteristic X rays and/or Auger electrons.

The γ decay process and the internal conversion process may be represented, respectively, as follows:

$$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + \gamma, and \tag{2.17}$$

$$^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X^{+} + e^{-} + {}^{A}_{Z}X \tag{2.18}$$

where

- $^{A}_{Z}X^{*}$ stands for an excited state of the nucleus $^{A}_{Z}X$.
- $^{A}_{Z}X^{+}$ is the singly ionized state of atom $^{A}_{Z}X$ following internal conversion decay.

An example of γ decay is the transition of an excited $^{60}_{28}$Ni nucleus, resulting from the β^{-} decay of $^{60}_{27}$Co, into stable $^{60}_{28}$Ni through an emission of two γ rays with energies of 1.17 and 1.33 MeV .

An example of internal conversion decay is the decay of excited $^{125}_{52}$Te* which results from an electron capture decay of ^{125}I into stable $^{125}_{52}$Te through emission of 35 keV γ rays (7%) and internal conversion electrons (93%).

2.8 Nuclear Reaction

Nuclear reactions and nuclear scattering are used to measure the properties of nuclei. Reactions that exchange energy or nucleons can be used to measure the energies of binding and excitation, quantum numbers of energy levels, and transition rates between levels.

A particle accelerator which produces a beam of high-velocity charged particles (electrons, protons, alphas, or heavy ions), creates these reactions when they strike a target nucleus. Nuclear reactions can also be produced in nature by high-velocity particles from cosmic rays, for instance in the upper atmosphere or in space. Beams of neutrons can be obtained from nuclear reactors or as secondary products when a charged particle beam knocks out weakly bound neutrons from a target nucleus. Beams of photons, mesons, muons, and neutrinos can also produce nuclear reactions.

In order for a nuclear reaction to occur, the nucleons in the incident particle, or projectile, must interact with the nucleons in the target. Thus the energy must be high enough to

overcome the natural electromagnetic repulsion between the protons. This energy barrier is called the **Coulomb barrier**. If the energy is below the barrier, the nuclei will bounce off each other.

Early experiments by Rutherford used low-energy alpha particles from naturally radioactive material to bounce off target atoms and measure the size of the target nuclei . When a collision occurs between the incident particle and a target nucleus, either the beam particle scatters elastically leaving the target nucleus in its ground state or the target nucleus is internally excited and subsequently decays by emitting radiation or nucleons. A nuclear reaction is described by identifying the incident particle, target nucleus, and reaction products [67].

The most important quantity of interest for a specific set of kinematic variables is the reaction cross section. The likelihood that a specific reaction will occur is shown by the cross section. This quantity, σ, which has the dimension of area, is measured by the experimental ratio [68].

2.8.1 Alpha Induced Reaction

The interaction of alpha particle with another nucleus results in induced nuclear reaction or coulomb excitation. The production of industrially and medically important radioisotopes called theranostic (therapeutic and diagnostic) radioisotope. Radioisotopes of ^{117m}Sn can be directly produced from the two highest mass number cadmium isotopes that is ^{114}Cd (α,3n) ^{117m}Sn and ^{116}Cd(α,3n) ^{117m}Sn reactions[57],[69].

2.8.2 Neutron Induced reaction

If a moving particle collide with another one, kinetic energy is exchanged between them in agreement with the laws of conservation of energy and of momentum. If the potential energy of the system remain unaltered, the kinetic energy being conserved during the collision, the phenomenon is called **Elastic scattering**. The scattering is **Inelastic** if one of the particle is left in an excited state after the collision.

The incident particle is captured and a "compound nucleus" is formed. which is either stable or radioactive. The mass of this compound nucleus is, however, smaller than the sum of the masses of the original nucleus and of the incident particle. Hence photons (prompt gammas) are emitted with an energy, determined by this mass difference, by the kinetic energy of the incident particle and the excitation levels of the compound nucleus. This phenomenon is usually called **Radiative capture**, represented by the (n,γ) reaction.At very high energy, spallation, fragmentation and fission of the compound nucleus is possible.

Absolute cross section measurements of neutron-induced reactions are cumbersome due to the neutron's reluctance to interact. Therefore, it is difficult to, e.g count all of the neutrons in a neutron beam. It is also difficult to create a neutron beam with specific properties since neutrons are difficult to direct and control. Direct measurements of the neutron cross sections are possible, e.g by utilizing neutron tagging , but more commonly

indirect measurements relative a neutron standard are made.

The neutron standards allow us to obtain cross sections for neutron-induced reactions on an absolute scale by measuring relative to another reaction with an assumed known **cross section**. Many different standards have been in use and there is not a single standard that is superior in all circumstances. So, one could ask what properties make a standard, **A standard** is a number of good properties for a neutron, The neutron standards according to IAEA and the energy ranges in which they are considered standards.

In addition to this list there are more requirements depending on what kind of reaction the neutron standard is based on and what kind of setup is used to measure it. However, no neutron standard is likely to have all the properties in the above list. Which property is the most important will depend on the specific situation. The requirements regarding other reaction channels as well as the size and structure of the cross section is highly energy dependent [70].

Table 2.4: Some examples of neutron standards according to IEAE and the energy range

Reaction	**Neutron energy range**
H(n,n)	1 kev-20 Mev
^{3}He (n,p)	thermal-50 Kev
^{6}Li(n,t)	thermal-1 Mev
^{10}B (n,α)	thermal-1 Mev
^{10}B (n,α,γ)	thermal-1 Mev
^{195}Au (n,γ)	thermal,0.2 Mev-2.5 Mev
^{235}U (n,f)	thermal,0.15 Mev-200 Mev
^{238}U (n,f)	2 Mev-200 Mev

2.8.3 Proton Induced Reaction

When protons and alpha particles in an astrophysical environment are accelerated to energies of a few MeV or greater, collisions with nuclei in the ambient medium can produce gamma rays when a nuclear reaction leaves the product in an excited state. In order to extract quantities such as the relative nuclear abundances and the energy spectra of the interacting particles from observed gamma ray spectra,it is necessary to know cross sections for the production of gamma rays in proton and alpha-particle induced reactions over a broad range of incident energies [71].

Some radioisotopes produced by proton induced effect are ^{201}Pb,^{111}In,^{18}F,^{11}C and others can be mentioned [72].

Deuteron ($^{2}_{1}$H) induce nuclear reaction can be seen under this scenario while it has a difference in it's atomic mass unit(2.01355 amu) when it compared with proton atomic mass(1.00727 amu) but both have possess positive charge.

2.8.4 Gamma Induced Reaction

Gamma rays are an electromagnetic radiation that have very small wavelength ranging 10^{-10} to $10^{-12}cm$. The ways of gamma-rays interact with matter and lose their energy are the photoelectric effect, the Compton Effect and pair production.

The examples of nuclear reactions produced by induced gamma radiation are illustrated below;

- γ + ^{63}Cu $\rightarrow$ ^{63}Ni^{+}p
- γ + ^{233}U $\rightarrow$ ^{90}Rb + ^{141}Cs + 2n

Therefore, in the first equation a γ-ray knocks a proton off ^{63}Cu, while in the second equation γ-ray induces nuclear fission of ^{233}U, with the production of two fragments and emission of two neutrons [73].

2.9 Terms of Nuclear Reaction

2.9.1 Nuclear Reaction Energy.

In the nuclear process X(x, y)Y the conservation of total energy indicates that;

$$(E_x + M_x C^2) + M_X C^2 = (E_Y + M_Y C^2) + (E_y + M_y C^2) \tag{2.19}$$

where:

- M_x: the incident particle's masses
- M_X: the intended nucleus
- M_Y: departing entity
- M_y: new formed atomic nucleus nucleus
- E : kinetic energies
- X : assumption target nucleus

The term **Q-value** refers to the variation in kinetic energy between the products and reactants.

$$Q = E_Y + E_y - E_x = (M_X + M_x - M_Y - M_y)C^2 \tag{2.20}$$

If $Q > 0$, then the reaction is exoergic (exothermic), with a net decrease in the products' rest mass and a net increase in their kinetic energy.

$Q < 0$, on the other hand, indicates an endoergic (endothermic) process in which energy is absorbed to raise the products' rest mass.

$Q = 0$ is a specific situation that only applies to elastic scattering, that is, where $M_x = M_y$ and $M_X = M_Y$. Since Y represents an excited configuration of the target nucleus X and $Q < 0$, in inelastic scattering, $M_x = M_y$ but $M_X > M_Y$.

2.9.2 Threshold Energy for Reactions

For nuclear reactions where the Q-value is negative, meaning the reaction is endothermic and requires an input of energy, the incident projectile particle must have a minimum amount of kinetic energy (E_x) before the reaction can take place. This minimum required energy for the incident particle is called **The total reaction threshold energy**.

Reaction threshold energies come in two varieties. These are Coulomb barrier threshold (E_c) and kinetic threshold energy (E_{thr}).

1. **THE KINETIC THRESHOLD ENERGY:** As it is present for both charged and neutral projectiles, the kinetic threshold energy, also known as the threshold energy, is charge independent. In fact, a nuclear reaction requires a little bit more energy than the Q-value to occur.

   This is because in any nuclear reaction, momentum as well as energy must be preserved. Based on the principle of conservation of momentum, a portion of the kinetic energy of the incident projectile particle is retained by the products of the reaction. Specifically, the fraction of the incident kinetic energy retained is given by the ratio of the projectile mass (M_x) to the total mass of the projectile and target nucleus ($M_x + M_X$).

   This means that only a fraction equal to $\frac{M_x}{M_x+M_X}$ of the incident particle's kinetic energy is actually available to drive the nuclear reaction.

   As a consequence, the minimum threshold energy required for the reaction to occur is higher than the Q-value alone. The full threshold energy is given by the expression:

   $$E_{thr} = \frac{-Q(1 + M_x)}{M_X} \tag{2.21}$$

2. **THE COULOMB BARRIER THRESHOLD:** A neutron or gamma photon, which are the incident projectile (x), can enter the target's nucleus without encountering any resistance. Thus, the threshold energy is the only minimal energy required to start a specific nuclear reaction.

   The circumstances will change, though, if the incident projectile is a positively charged particle. The projectile is repelled by Coulombic nuclear forces as it gets closer to the target nucleus; if it lacks enough momentum, it will not be able to enter

the target nucleus.

Nuclear forces cannot interact between the two particles and result in a nuclear reaction until the projectile touches the target nucleus' surface.Therefore, even in the case of a reaction with a positive **Q**- value, the reaction cannot occur even if the reaction's energy and momentum limitations are met by a positively charged incident projectile that lacks the kinetic energy to reach the target nucleus.

After a distance (r) between the impacting projectile (charge $Z_x e$) and the target nucleus (charge $Z_X e$), the Coulombic repulsive potential between them is

$$E_c = \frac{Z_X Z_x e^2}{4\pi\epsilon_0 r} \tag{2.22}$$

where : ϵ_0 is Free space's permittivity.

On the other hand, we can roughly estimate at contact that

$$r = R_x + R_X = R_0(A_x^{1/3} + A_X^{1/3}) \tag{2.23}$$

where:

- R_x : radii of the incident projectile
- R_X : radii of the target nucleus
- A_x : the number of the target nucleon
- A_X : the number of the projectile
- $R_0 \approx 1.25 \times 10^{-13} cm$

Therefore, an impacting particle with a positively charged nucleus needs to have a kinetic energy of about to break through the Coulomb barrier and interact with the target nucleus (after changing the constants to the necessary values).

THE OVERALL THRESHOLD ENERGY: No Coulomb barrier needs to be broken for a neutral incident particle (such as a neutron or photon) in order for the reaction to occur. As for exoergic reactions, there is no threshold ($Q > 0$). The kinematic threshold energy is the only threshold for endoergic reactions ($Q < 0$). Nonetheless, the Coulomb barrier must always be broken for impacted particles having a charged nucleus.

The only threshold that exists for exoergic reactions ($Q > 0$) is the Coulomb barrier threshold E_c.The endoergic reactions $(Q < 0)$ have both Coulomb and kinematic thresholds. [74].

2.9.3 Reaction Cross-Section

One of the most important physical quantities characterizing the properties of nuclear reaction is the total nuclear reaction cross section. It is very useful for extracting fundamental information about the nuclear size and the density distributions of neutrons

and protons in nucleus. In particular, the neutron halo has been found by measuring the total reaction cross section induced by radioactive nuclear beams [75].

Cross section is commonly measured in units of barns:

$$1barns = 10^{-28}m^2 or 10^{-24}cm^2$$

The likelihood of a specific reaction occurring is expressed as the cross section. This quantity, σ , which has the dimension of area, is measured by the experimental ratio: number of reaction particles emitted per the number of beam particles per unit area times number of target nuclei within the beam.

The product of each target nucleus cross section and the total number of target nuclei in the target sheet determines whether nuclear reactions can occur.

$$\textbf{The available nuclear target area} = (NSd)\sigma \tag{2.24}$$

where:

- N: number of incident particle
- S: total area
- σ: nuclear cross section

The ratio of this area to the total area (S) provided to the incident particle determines the chance, for one incident particle to strike a nuclear target region. Therefore

Probability of interaction per particle = (overall target area divided by nuclear target area)

$$= \frac{(NSd)\sigma}{S} = Nd\sigma \tag{2.25}$$

On the other hand cross section can be explained as the effective area exposed to the beam per target for which a specific reaction likely to occur and differential cross section ($\frac{d\sigma}{d\Omega}$) applicable to provide essential data on the angular distribution of the reaction products [76].

The cross-section depends on the target particle, i.e, the type of particle being accelerated and the composition of the rest gas. In addition there is often dependence on a strong energy and on the type of interaction that is involved. Cross-section plays an important role in the production of radioisotopes. The differential cross section is given by:

$$\frac{d\sigma}{d\Omega}(E,\Omega) = \frac{(1/F) \times dN_s}{d\Omega} \tag{2.26}$$

Where $\frac{d\sigma}{d\Omega}$ is the average fraction of the particles scattered into $d\Omega$ per unit time per unit flux F, N_s is the average number scattered per unit time [73].

The constant proportionality of cross section has dimensions area and given by:

$$\sigma_i = \frac{W_i}{n_j \sigma_x} \tag{2.27}$$

This equation can be rewritten as follows:

$$N_{target} = nA\sigma \times J, P_{Scatt} = \frac{\sigma}{A} \tag{2.28}$$

$$W_i = (nA\sigma x)J\frac{\sigma}{A} \tag{2.29}$$

$$W_i = \frac{N_{target}}{P_{scattered}} \tag{2.30}$$

Where, W_i is the rate of reaction proportional to flux of incoming projectiles, J is the quantity for each time unit ,n is number density of scattering centers in the target and x the width of the target number per unit volume. While, A is the area of the target and N_target is the total number of targets illuminated by the projectile.

The total cross section of integrated angle can be given by;

$$\sigma_\alpha = \int \frac{d\sigma_\alpha \Omega}{d\Omega} d\Omega \tag{2.31}$$

2.9.4 Stopping Power

The slowing or loss of kinetic energy of a charged particle when it traverses through matter or target per unit length is regarded as the stopping power and is given by:

$$S = -\frac{dE}{dx} \tag{2.32}$$

The value of $-\frac{dE}{dx}$ along a particle track is also called its specific energy loss or, its rate of energy loss. For particles with given charge, S is inversely proportional with the particle velocity.

The specific energy loss is expressed as described by Bethe formula and is written as follows:

$$\frac{dE}{dx} = (\frac{4e^4 Z^2}{m_0 v^2})NB \tag{2.33}$$

$$B = Z[\ln(\frac{2m_0V^2}{I}) - \ln(1 - \frac{V^2}{C^2}) - \frac{V^2}{C^2}] \tag{2.34}$$

Where,

- v : velocity
- N : number density
- Z : atomic number of the absorber atoms
- m_0 : the electron rest mass
- e : electronic charge [76].

Therefore, the stopping power of a heavy charged particle by using relativistic quantum mechanics of Bethe derived is given by the following expression [77];

$$\frac{-dE}{dx} = (\frac{4e^4K0^2nZ^2}{m_0v^2})[\ln(\frac{2m_0v^2}{I}) - \ln(1 - \frac{v^2}{C^2}) - \frac{V^2}{C^2} \tag{2.35}$$

2.9.5 Production Yield of Nuclear Reaction

The yield of a nuclear reaction is defined as the ratio between the number of product nuclei formed and the number of incident particles striking the target. This ratio represents the physical yield (Y) of the reaction, and it can be used to characterize the efficiency or productivity of the reaction for targets of any thickness.

The physical yield of a nuclear reaction is expressed in the unit of Becquerel per Coulomb (Bq/c). This unit represents the ratio between the radioactive activity produced (in Becquerels) and the total electric charge (in Coulombs) of the incident particles.

The analytical interpretation of the physical yield is that it represents the initial slope of the curve showing the growth of radioactive activity of the produced radionuclide over the irradiation time. This slope provides a quantitative measure of the rate at which the radioactive product is being formed at the beginning of the irradiation process.

$$\frac{dA(t)}{dt}|_{t=0} = N_0\sigma\Phi\lambda \tag{2.36}$$

Since radioisotopes undergo radioactive decay during the bombardment process, other yield definitions are used in practical applications that account for this disintegration.

One such metric is the ($1h1\mu A$yield), denoted as(A_1), which represents the radioactive activity of the produced isotope at the end of a 1-hour bombardment with a constant beam

current of $1\mu A$.

This $1h1\mu A$yield is closely related to the actual measured activity in everyday isotope production using accelerators, providing a more practical and relevant yield definition compared to the basic physical yield.

In real-world applications, this latter number can be employed in situations when the bombardment duration is either much less than or equivalent to the half life of the generated isotope.

$$A_1 = N_0\sigma\Phi(1 - e^{-\lambda t_i}) \tag{2.37}$$

When the irradiation time is much longer than the half-life of the produced isotope $(1 - e^{(-\lambda t)} \approx 1)$, a saturation of the number of the radioactive nuclei present in the target is reached, and their activity becomes practically independent of the bombardment time (at a constant beam current). This activity produced by a unit number of incident beam particles is the so-called saturation yield, A_2.

$$A_{sat} = A_2 = N_0\sigma\Phi \tag{2.38}$$

Because of the relatively slow approach to the saturation (A_{sat}), it is generally accepted that in practice, irradiation times beyond ($2t_{1/2}$) are not worthwhile. There are close relationships between the above-mentioned yields. Using the decay constant of the radionuclide (λ) and the irradiation time (t_i) one gets

$$Y = A_1\frac{\lambda}{(1 - e^{-\lambda t_i})} = A_2\lambda \tag{2.39}$$

If the irradiation time is too shorter than the half life of the produced isotope the quantity ($e^{(-\lambda t)} \approx 1 - \lambda t$) and hence, the growth of the activity will be rapid and almost linear with time.

$$A = N_0\sigma\Phi\lambda t_i \tag{2.40}$$

The amount of radioisotope produced by a particular nuclear reaction in a target can be estimated by integrating its excitation function over the range of beam energies and over the target material when a projectile impinged on a target slows down as it penetrates the media. A thick target yield Y is the efficiency of production route, therefore it associated to the beam stopping power and the yield can be defined as given below [77]:

$$Y = \left(\frac{N_A F}{M}\right) I_b(1 - e^{-\lambda t}) \int_{E_i}^{E_{th}} (\sigma(E)\frac{dE}{dx})\, dE \tag{2.41}$$

Where:

- M-atomic mass weight of the target material.
- F-the fraction of the target isotope.
- N_A-is the Avogadro constant number (6.022045×10^{23} atoms per mol),
- I_b-is beam current and $\frac{dE}{dx}$ represents the target stopping power.

Most target systems produce actual yields that are typically lower than their theoretical estimates. This is especially true for gas target systems. Possible reasons for low yield at high beam currents in gas targets could be the interaction of the produced radionuclide with the target chamber walls, gas density reduction due to beam heating of the gaseous target material and thus the lack of optimization of the energy of the projectile. It has been clearly demonstrated that gas density reduction is a major contributor to loss of yield as a function of beam current [78].

In order to optimize the production of a particular radionuclide the following production considerations must be taken into account:

- the threshold energy for the desired reaction
- the energy where the maximum yield occurs,
- the chemical form of the target nucleus,
- the physical form of the target nucleus,
- the chemical form of the desired product,
- the physical form of the desired product, and
- the ease of separation of product from the target.

2.10 Problems Related to Use of Radionuclide

It is widely accepted that the behavior of radioisotopes in the environment, their uptake by living organisms, and their toxicity are primarily determined by their physical and chemical properties, particularly their "speciation" or chemical form. The gross concentration of the radioisotopes is a less significant factor compared to their speciation in determining environmental behavior and biological impacts.

The initial chemical speciation of a radionuclide (as well as a non-radioactive element) is heavily influenced by its source or origin. However, the subsequent fate and behavior of the nuclide is then largely determined by the physical and chemical properties of the surrounding environment.

For example, the mobility of a radionuclide within an aquifer (groundwater system) depends strongly on factors such as whether the nuclide has a neutral, negative, or positive electrical charge, as well as the composition of the mineral surfaces and dissolved chemical species present in the aquifer.

These environmental characteristics play a crucial role in dictating how the radionuclide will interact with and move through the aquifer, rather than just its initial chemical form upon release. The speciation and environmental conditions together govern the ultimate fate and transport of the radioisotope. [79].

The suitable physical half-life of therapeutic radionuclide ranges from 6 h and 7 d. The challenge of short physical half-life is limitation of delivery flexibility and is very impractical, whereas a long half-life will retain in the patients and expose surrounding tissue to the radiation for a longer period.

Long physical half-life increases treatment cost, since the patients need to be admitted and isolated for a longer period, while the biological half-life depends on the tracer used. Long physical half-life radionuclide ordered for slow uptake since the radionuclide will not decay completely before it reaches the targeted tumor.

Some examples of health hazard due to radioisotopes;

1, Chronic Effects (Non cancer):

- Uranium overdose exposer may cause kidney dis-function
- Chronic exposure to radium in humans, by inhalation, has resulted in acute leukopenia, while oral exposure has resulted in anemia, necrosis of the jaw, abscess of the brain, and terminal bronchopneumonia.
- Chronic exposure to radon in humans and animals via inhalation has resulted in respiratory effects (chronic lung disease, pneumonia, fibrosis of the lung, decreased lung function), while animal studies have also reported effects on the blood and a decrease in body weights [80].

2, Reproductive/Developmental Effects:

- it is important to determine if, at a high enough systemic exposure to Co, reproductive effects could occur in patients with Co-containing medical devices. High systemic Co exposures have been reported to result in detrimental effects in animals and/or humans, including adverse hematological, neurological, immunological, reproductive, cardiovascular, and endocrine responses [81].
- **Sperm quality/motility:** A reduction in sperm quality as indicated by sloughing off dead and degenerating spermatogenic and Sertoli cells, reduced sperm motility, reduced sperm concentration, increased abnormal sperm, and lateral amplitude in sperm (a sperm motility parameter) (Bucher et al., 1990; Chen et al., 2013; Corrier et al., 1985; Pedigo et al., 1988; Pedigo and Vernon, 1993).

3, Cancer Risk:

- Radium and radon are potent human carcinogens.Radium, via oral exposure, is known to cause lung, bone, head (mastoid air cells), and nasal passage tumors. Radon, via inhalation exposure, causes lung cancer.
- Smokers exposed to radon are at greater risk for lung cancer (approximately 10 to 20 times) than are nonsmokers similarly exposed.
- Studies in uranium miners have shown an increase in lung cancer and tumors of the lymphatic and hematopoietic tissues from inhalation exposure. However, it is not known whether the cancer risk is from uranium itself, or from radon or other confounding factors.

CHAPTER 3
MATERIALS AND METHODOLOGY

There are different computer codes to calculate the theoretical excitation functions, as such PACE4, CASCADE, ALIC-91 and COMPLET codes can be mention while for this paper work PACE4 statistical model code used to compute the excitation functions of the selected radioisotope .

The statistical model code PACE4 (Projection Angular Momentum Coupled Evaporation 4) is a modified version of JULIAN, the HillmanEyal evaporation code using a Monte Carlo code coupling angular momentum. The program has been ported to Windows from FORTRAN to C^{++} and incorporated in the $LISE^{++}$ package under the name PACE4. PACE4 uses Monte Carlo procedure to determine the decay sequence of an excited nucleus using the Hauser Feshbach formalism [82].

The main advantage of Monte Carlo calculations is to provide correlations between various quantities, such as particles and gamma-rays or angular distribution of particles. Sequential decays are considered until any further decay is prohibited due to the energy and angular momentum conservation laws.

A random number selection determines the actual final state to which the nucleus decays to and the process is, then, repeated for other cascades until all the nuclei reach the ground state . However, PACE4 predictions were found to be in good agreement for complete fusion channels projectile-target system and is appropriate for heavy ion induced reactions.

The angular momentum projections are calculated at each stage of de-excitation, which enables de-excitation of the angular distribution of the emitted particles. The transmission coefficients for light particle emission (n, p,d and α) are determined using optical model potentials.

The code also provides event-by-event trace back of the entire decay sequence from the compound nucleus into any one of the exit channels. The fusion cross sections are obtained from the Bass model.The fission probability is calculated using the Bohr-Wheeler saddle point formalism.

The PACE4 code has the ability to provide information on energy and angular distributions of evaporated particles.The partial cross section for compound nucleus formation at angular momentum "l" and specific bombarding energy is given by [83]:

$$\sigma_l = (\frac{\lambda^2}{4\pi})(2l+1)T_l \tag{3.1}$$

where λ is the reduced wavelength and T_l is the transmission coefficient given by:

$$T_l = (1 + exp(l - l_{max})/\delta) \tag{3.2}$$

where δ is the diffuseness parameter and l_{max} is maximum angular momentum and determined by the total fusion cross section σ_F can be obtained by[84]:

$$\sigma_F = \sum_{l=0}^{\infty} \sigma_l \tag{3.3}$$

and here the level density Parameter is an important parameter which may be varied to match the experimental data. The Level density parameter obtained by experiment shows a linear dependent with the mass number of the compound nucleus. In general it is given by an expression;

$$a = \frac{A_{CN}}{K} \tag{3.4}$$

Where A_{CN} is the mass of the compound nucleus and K is the free constant. The level density parameter is found to play an important role in the theoretical predictions. The theoretical calculation of excitation function is performed at level density parameters;

$$a = \frac{A_{CN}}{8}, a = \frac{A_{CN}}{10} and a = \frac{A_{CN}}{12} \tag{3.5}$$

And the other controlled parameter is number of cascades(events in monte carlo calculation), is set at **NCASC** = 100,000.

CHAPTER 4
RESULT AND DISCUSSION

4.1 Analysis of Nuclear Reactions

This thesis paper discuses about deuteron induced nuclear reaction of four selected target radioisotopes that are considered for the production of medically important radioisotopes (^{124}Te(d,n)^{125}I,^{63}Cu(d,3n)^{62}Zn,^{14}N(d,n)^{15}O and ^{103}Rh(d,2n)^{103}Pd) and the theoretical computed excitation function by the statistical model code of PACE4 evaluated and compare with the experimental registered excitation function data taken from IAEA(International Atomic Energy Agency).

4.1.1 Production of Iodine-125

Due to Iodine-125 suitable longer half-life (59.4 days) and less penetrating gamma spectrum(with medium energy of 29 keV), is also often preferred for laboratory tests that rely on Iodine as a tracer that is counted by a gamma counter, such as in radio immunoassaying [85]. Brachytherapy using iodine-125 seeds has been used in prostate cancer treatment. The prostate tumor may be treated by different methods, including brachytherapy. By this technique, small iodine-125 seeds are implanted in the prostate, giving a high radioactive dose to the target and preserving the healthy neighbor tissues. [86].

Among these advantages are the longer half-life of iodine-125 , which results in a greatly increased shelf-life of tagged compounds, and the lower energy of its radiations, which reduces shielding requirements and permits more efficient detector design[87].

The most useful reaction for the production of Iodine-125 is ^{124}Te(d,n)^{125}I. Evaluated excitation function is taken from ENDF library and the recommended excitation functions have been calculated by evaluating the cross section with PACE4 statistical model code by fitting level density parameter at "K" = 8,10,and 12.

This evaluation is used to calculate the integral yield of radioactive Iodine-125. For the production of ^{125}I the energy range is considered from 4.5 Mev to 20 Mev for both evaluated and theoretical excitation function evaluation.

Tabulated data for the production of Iodine-125 with different energy level and level density(K) is presented as shown below.

Table 4.1: Variation of nuclear cross section(mb)on Deuteron energy (Mev)for ^{124}Te(d,n)^{125}I:Evaluated ENDF data and calculated PACE4 data

Energy(Mev)	**ENDF DATA(mb)**	**K=8 (mb)**	**K=10 (mb)**	**K=12 (mb)**
4.5	0.1	0	0	0
5.5	23.5	0	0	0
6.5	92	0	0	0
8	211	260	260	259
9	232	496	508	513
9.5	225	505	540	555
11	176.4	176	232	279
11.5	160.6	160	213	260
13	126.3	39.5	54.2	93
14.5	98.4	14.7	28.3	41.7
15.5	83	7.5	13.5	23.1
17	68.7	2.11	4.4	7.59
18.5	58.5	0.99	2.06	4.42
19.5	53.3	0.56	1.17	2.32
20	51.3	0.298	0.613	1.46

Experimental excitation function of deuteron-induced ^{124}Te(d,n)^{125}I reaction considers the energy range from 4.5 Mev-20 Mev while PACE4 statistical model give a cross section result beyond energy range 7.5 Mev because of the unavailability of the excitation function value at energy less than 8 Mev.

These stated data described graphically as shown:

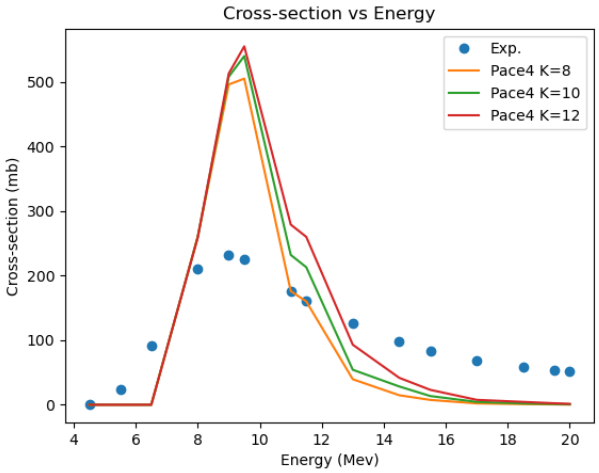


Figure 4.1: Graphical expression of Iodine-125 production data.

The evaluated excitation function result is compared with theoretical estimated values of PACE4 at 3 different level density parameters(K=8,K=10, & K=12), the highest cross-section value is around 8 Mev-9 Mev. At 9 MeV of deuteron incident energy, the maximum evaluated nuclear cross-section is 232 mb and theoretically, 505 mb at 9.5 Mev deuteron incident energy for K=8, 540 mb at 9.5 Mev deuteron incident energy for K=10, & 555 mb at 9.5 Mev deuteron incident energy for K=12.

As we can see from stated data description, the experimental data and computed theoretical data is not exactly fitted through out the all energy ranges. At lower energy range (8.0 Mev-11.5 v) the experimental data is much fit with the data generated at density parameter K=8, afterward this energy range much better result is found at K=12.

4.1.2 production of Zinc-62

Cyclotron-produced Zn-62, a positron emitter, has potential application to positron reconstruction tomography in the imaging of the pancreas or prostate [88].

The zinc-62-copper-62 (^{62}Zn-^{62}Cu)[^{62}Zn: $T_{1/2} = 9.2hr$,]) generator system is considered to be one of the most desirable labeling sources for radio pharmaceutical [89]. For the production of ^{62}Zn the energy range is taken from 17 Mev to 35 Mev for both evaluated and theoretical excitation function evaluation,tabulated data and graphical expression of the production of Zinc-62 is stated below as shown:

Experimental excitation function of deuteron-induced ^{63}Cu(d,3n)^{62}Zn reaction considers the energy range from 17 Mev -35 Mev while PACE4 statistical model give a cross section result beyond energy range 21.5 Mev because of the unavailability of the excitation function value at energy less than 22 Mev.

Table 4.2: Variation of nuclear cross section(mb)on Deuteron energy (Mev)for $^{63}Cu(d,3n)^{62}Zn$:Evaluated ENDF data and calculated PACE4 data.

Energy	ENDF DATA	K=8	K=10	K=12
17	0.4	-	-	-
19	1.0	-	-	-
20	2.8	-	-	-
22	9.4	0.357	0.119	-
22.5	11.4	0.793	0.0828	0.0355
24	18.1	4.566	1.36	0.801
26	28.0	16	8.53	5.83
27	33.1	24	15.5	10.9
28.5	38	38.5	29.7	23
30	46	44.3	37.6	32.8
31	48.7	49	42.7	37.9
32	50.2	52.5	46.2	41.3
33	50.5	55.8	51.6	47.1
34.5	49.4	63.9	61.1	54.6
35	49.1	59.8	58.2	53.5

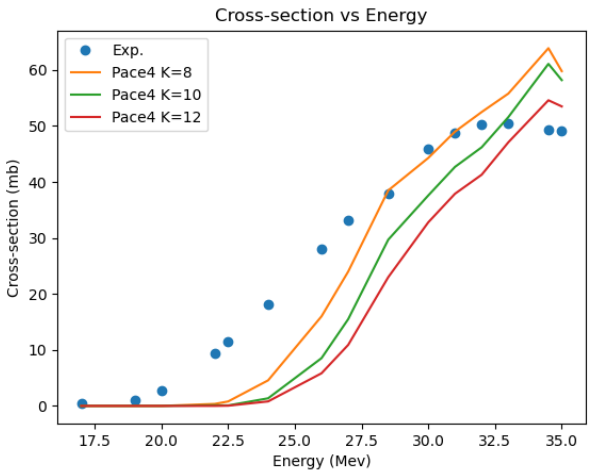


Figure 4.2: Graphical stated data of Zinc-62 production.

The evaluated excitation function result were compared with theoretical estimated values of PACE4 , the evaluated data has the highest cross-section value around 33 Mev-35 Mev. At 33ÂăMeV of deuteron incident energy, the maximum evaluated nuclear cross-section is 50.5 mb and theoretically, 63.9 mb at 34.5 Mev deuteron incident energy for K=8, 61.1 mb at 34.5 Mev deuteron incident energy for K=10, & 54.6 mb at 34.5 Mev deuteron incident energy for K=12

In this nuclear reaction scenario the theoretical generated data is highly fit with the experimental data at density parameter K=8.

4.1.3 production of Oxygen-15

The radionuclide oxygen-15, half-life 2.05 min, is used in simple chemical forms to study oxygen metabolism, blood flow and blood volume in man,using the technique of positron

emission tomography (PET) [90]. Oxygen-15 labeled gases Due to the extremely short half life,Oxygen, an essential molecule for life, is utilized not only for cellular respiration but also for biosynthesis and metabolism of various important biomolecules such as steroids, eicosanoids, and neuroactive substances[91].

Tabulated data for the production of oxygen-15 through a nuclear reaction ^{14}N (d,n) ^{15}O is stated below with corespondent to the experimental data and explained more graphically.

Table 4.3: Variation of nuclear cross section(mb)on Deuteron energy (Mev)for ^{14}N (d,n) ^{15}O: Evaluated ENDF data and calculated PACE4 data.

Energy	ENDF DATA	K=8	K=10	K=12
1	10	0	0	0
1.5	25.5	0	0	0
2.5	134.6	44.4	29.6	92.2
3.5	213	56.5	37.6	196
4.5	205	72.9	59	197
6.5	173	91.6	61.2	72.3
8	143.4	93.6	64.3	91.4
10	109.1	89.1	91.6	83.1
12.5	79.6	94.4	77.6	214
13.5	71.1	75.2	69	210
15	60.9	56.6	53.9	88.6
16	55.4	48	53.7	60.1
17.5	48.7	40.2	44.1	39.8
18.5	44.9	39.8	37.8	37.4
20	40.2	26.9	30.7	32.7

Graphically the data stated above can be described as:

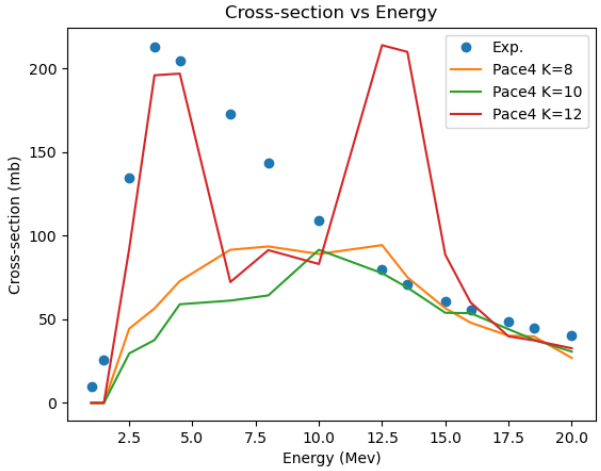


Figure 4.3: Graphical expression of Oxygen-15 production data.

Experimentally recorded excitation function of deuteron-induced ^{14}N(d,n)^{15}O reaction considers the energy range from 1 Mev-20 Mev while PACE4 statistical model give a cross

section result beyond energy range 2.5 Mev because of the unavailability of the excitation function value at energy less than 2.5 Mev.

The evaluated data has the highest cross-section value is around 3.5 Mev-6.5 Mev energy of the deuteron incident energy.At 3.5ÂăMeV of deuteron incident energy, the maximum evaluated nuclear cross-section is 213ÂămÂăb and theoretically, 12.5 mb at 34.5 Mev deuteron incident energy for K=8, 91.6 mb at 10 Mev deuteron incident energy at for K=10, & 214 mb at 12.5 Mev deuteron incident energy for K=12.

The tabulated data and graphical description shows that in this reaction the data generated is not constantly fit with the experimental one, but we clearly see at energy range from 10.0 Mev to 20.0 Mev the data is better fitted at K= 10.

4.1.4 Production of palladium-103

Excitation functions for the deuteron induced reactions on ^{103}Rh is an alternative pathway for the production of the medically used ^{103}Pd, Experiments made at incident energies of 6.5 and 23.5 MeV allowed reliable determination of the cross sections for ^{103}Pd [92]. ^{103}Pd ($T_{1/2} = 16.991$ days) is one of the common used radioisotopes for suitable for interstitial brachytherapy: encapsulated in millimeter-size seed implants it is used in prostate, breast or choroidal melanomas cancer brachytherapy. It is a x-ray emitter(21-23KeV) [93].

Tabulated cross section and graphical representation of ^{103}Rh(d,2n)^{103}Pd from ENDF and theoretical PACE4 results are stated below:

Table 4.4: Variation of nuclear cross section(mb)on Deuteron energy (Mev)for ^{103}Rh(d,2n)^{103}Pd: Evaluated ENDF data and calculated PACE4 data.

Energy	ENDF DATA	K=8	K=10	K=12
6.5	199	0	0	0
7	279	30.5	26.7	24
8.5	564	293	263	240
9.5	741	584	534	474
11	932	931	883	831
12.5	1034	1120	1080	1030
13.5	1056	1200	1180	1140
15.5	989	1320	1290	1260
18	725	1390	1360	1330
19	601	1340	1330	1340
20	488	1100	1170	1320
21.5	353	758	885	1130
22.5	288	522	656	915
23	262	370	501	745
23.5	239	337	468	707

Experimental excitation function of deuteron-induced ^{103}Rh(d,2n)^{103}Pd reaction considers the energy range from 6.5 Mev - 23.5 Mev while PACE4 statistical model give a cross

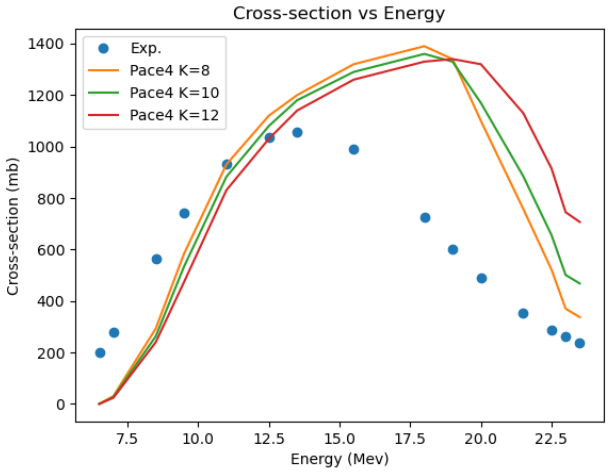


Figure 4.4: Graphical expression of Palladium-103 production data.

section result beyond energy range 6.5 Mev because of the unavailability of the excitation function value at energy less than 7 Mev.

The evaluated data has the highest cross-section value is around 12.5 Mev-15.5 Mev energy of the deuteron incident energy , maximum evaluated nuclear cross-section is 1056 mb at 13.5 Mev deuteron incident energy of and theoretically, for K=8, highest cross-section value is around 15.5 Mev-19 Mev energy of the deuteron incident energy, with maximum cross-section 1390 mb at 18 Mev incident energy, for K=10, highest cross-section value is around 15.5 Mev-19 Mev energy of the deuteron incident energy, with maximum cross-section 1360 mb at 18 Mev deuteron incident energy and for K=12, highest cross-section value is around 18 Mev-20 Mev energy of the deuteron incident energy, with maximum cross-section 1340 mb at 18 Mev deuteron incident energy.

From energy range, 7.0 Mev to 11.0 Mev at density parameter K=8 and for energy range 12.5 Mev to 15.5 Mev at K= 12 is better data has manipulated but it is far to be fitted with the experimental data.

CHAPTER 5
CONCLUSIONS

In this study, theoretical excitation functions of $^{124}Te(d,n)^{125}I$, $^{63}Cu(d,3n)^{62}Zn$, $^{14}N(d,n)^{15}O$ and $^{103}Rh(d,2n)^{103}Pd$ nuclear reaction has been computed using PACE4 code.These calculated theoretical excitation functions were compared with ENDF(Evaluated nuclear data file) IAEA database data.

In the production of medically important radioisotopes Iodine-125 ($^{124}Te(d,n)^{125}I$) and Oxygen-15 ($^{14}N(d,n)^{15}O$) higher cross-sections found at lower energy range while in the production of medically important radioisotopes of Zinc-62 ($^{63}Cu(d,3n)^{62}Zn$)and palladium-103 ($^{103}Rh(d,2n)^{103}Pd$) higher cross-sections obtained at higher energy range.

In these reaction the theoretical output result is not well fitted with the experimental data, this is due to, the contribution from the incomplete fusion reaction, pre-equilibrium fusion and light particle reaction is not well taken into account by PACE4 statistical model code.

Thus from the above analysis, the statistical model code(PACE4) mainly consider complete fusion (CF) and the reaction takes place between large mass particles, and experimental and theoretical cross-sections are in good agreement in this reaction scenario while incomplete fusion and light particle reaction has not well recognized and not taken to be measured by this model of statistical code model,However the experimental and theoretical excitation function is less agree to be fit.

Recommendation

To compute better and more reliable theoretical excitation function data which highly match with the experimental ENDF data, this paper recommend that PACE4 statistical model code has to upgrade it's model to advance on incomplete fusion, pre-equilibrium fusion and light particle reaction and other reaction situation which are important for computing more precise output values.

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DECLARATION

ADDIS ABABA UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES
DEPARTMENT OF PHYSICS

MSc Thesis

Evaluation Of Reaction Cross-Section For Deuteron Induced Radioisotope [^{125}I,^{62}Zn,^{15}O And ^{103}Pd] At Different Energy Ranges Using the PACE 4 Code

Name of Candidate: Anteneh Getachew Abeje

I the under signed declare that the thesis is my original work and no part of it can be claimed as an intellectual property of anybody else except me and my advisors.

Signature: _____

June 19, 2024