NEUTRONS AND PRODUCTION OF NEUTRONS OF VARIOUS ENERGY

By

AWEL ABDELA HUSEN

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The under signed hereby certify that they have read and recommendded to the school of Graduate Studies for acceptance a Project entitled "NEUTRONS AND PRODUCTION OF NEUTRONS OF VARIOUS ENERGIES"by AWEL ABDELA HUSEN in partial fulfillement of the requirements for the degree of Masters of science in Physics.

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Supervisor: ______________________
PROF.A.K.CHAUBEY

Examiners: ______________________
DR.TILAHUN TESFAYE

____

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Author: **AWEL ABDELA HUSEN**

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Signature of Author

DEDICATED TO

My dad,Abdela Husen

It would have been very nice and i could have got more happiness,if you were here with me...love you dad!

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Acknowledgements

All the praises and thanks are to ALLAH, the Lord of mankind, jinn, and all that exists.

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Abstract

Neutrons are normally bound into an atomic nucleus, and do not exist free for long in nature. The unbound neutron has a half-life of just under 15 minutes. The release of neutrons from the nucleus requires exceeding the binding energy of the neutron, which is typically 7-9 MeV for most isotopes. Neutron sources generate free neutrons by a variety of nuclear reactions, including nuclear fission and nuclear fusion. Whatever the source of neutrons, they are released with energies of several MeV.

Neutrons are found bounded inside a nucleus of an atom, almost all elements in periodic table contains at least one neutron bounded inside their nucleus except ordinary hydrogen atom which contains only one proton inside its nucleus. Free neutrons do not occur naturally, so they have to be created artificially. If one needs neutrons of different energy for any purpose he should extract neutrons from the nucleus of certain element by imparting energy to it.The minimum energy needed by a nucleus to emit one neutron is nearly equal to the binding energy of a neutron, approximately around 7Mev. As neutral particles with an average lifetime of 15 minutes they cannot be stored or accelerated like charged particles. Therefore neutrons have to be created with energies higher or equal of the intended treatment energy.

Chapter 1

Introduction

1.1 Discovery

The existence of the neutron was first suggested by Rutherford in 1920. Being electrically neutral, the neutron was very difficult to discover by methods of particle detection, which depend on the deflection of the particles in a magnetic or electric field or on their ionization of matter. In 1932, however, one of Rutherfords students, Chadwick, demonstrated the existence of the neutron, using an experiment first conducted by Bothe and Becker in 1930 and later by Irene and Frederic Joliot [1]. In the experiment,a beryllium plate (Be) was bombarded by α particles from a polonium source. This caused highly penetrating radiation to emanate from Be. Irene Curie and her husband discovered that when a beam of this radiation hit a substance rich in protons, for example paraffin, protons were knocked loose(as shown in figure 1.1) which could be easily detected by a Geiger counter.Chadwick showed conclusively that the penetrating radiation could not be γ ray photons, as was initially suspected, but was that of a neutral particle, roughly equal in mass to the nucleus of the hydrogen atom (proton).

In his experiment,when a sheet of paraffin wax was interposed between the target and the ionization chamber, and the maximum range and velocity of protons were determined.He was doing this experiment many times and also for nitrogen too(see figure 1.1).

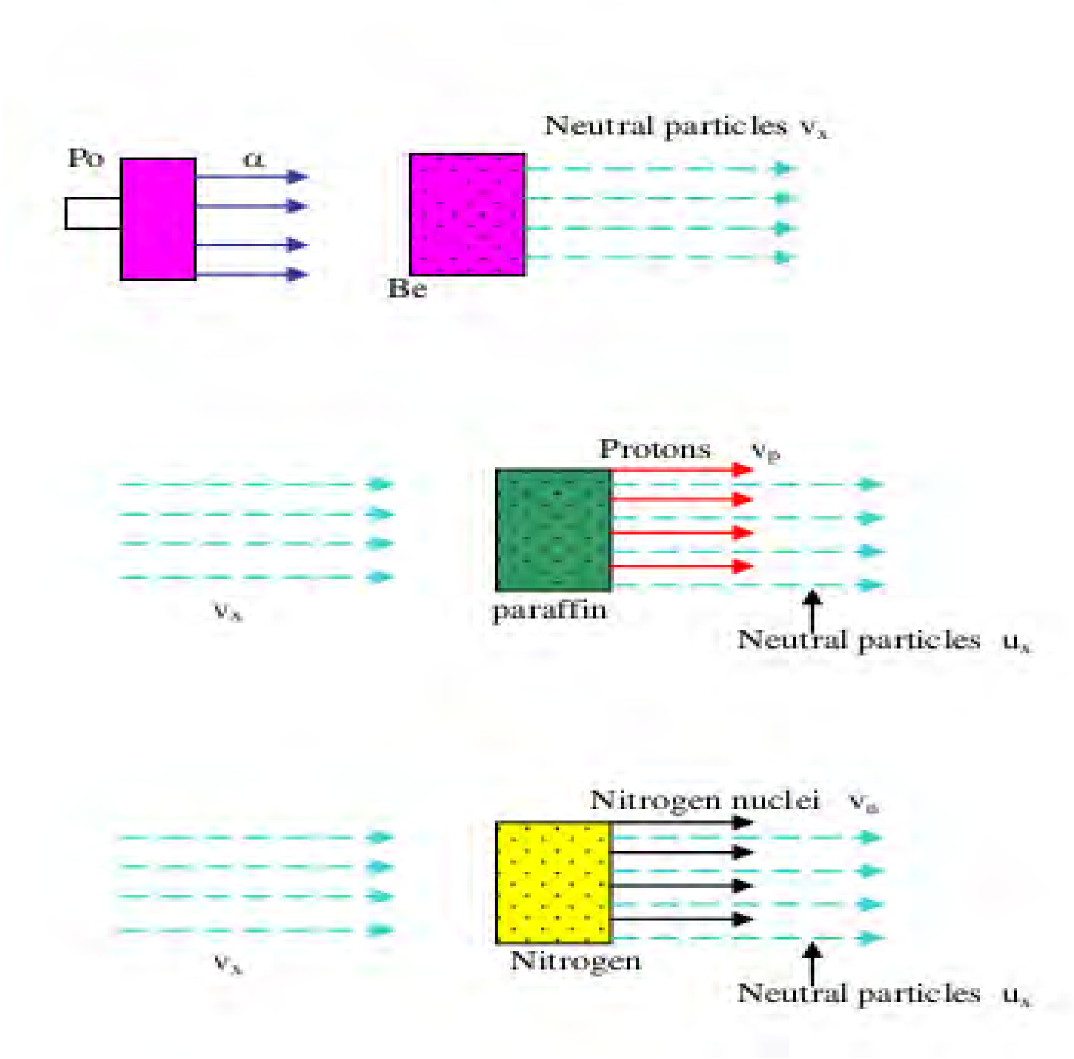

Figure 1.1: Experimental analysis of Curie and Joliet,later by chadwick [10]

By measuring the velocities with which protons were ejected from various materials and utilizing simple collision theory, it was possible for Chadwick to determine the mass of this new particle and show that it was close to the mass of a proton. He thus demonstrated that Rutherfords concept of the existence of the neutron was correct[3].

Showing that the mass of the neutron is a little greater than the mass of the proton a later and more accurate measurement showed that the neutron mass is extremely close to that of the proton.

After demonstrating the existence of new particle and measuring its mass,He assumed that the radiation consisted of particles of zero charge and mass about equal to proton, Chadwick named it the “neutron” [1].

Thus, neutrons are emitted when beryllium absorbs an α according to the following reaction.

$$^{4}_{2}He +^{9}_{4} Be \rightarrow^{1}_{0} n +^{12}_{6} C \tag{1.1.1}$$

In 1932, Chadwick proposed that this particle was Rutherford’s neutron. In 1935, he was awarded the Nobel Prize for his discovery.

1.2 Properties Of Neutrons

First of all, neutrons are uncharged particles,it is electrically neutral. Much like photons, they can penetrate several centimeters of target material without interacting [1].

The second property is that their interactions are with the nuclei of absorbing material. It doesnt interact with electrons to any large degree. Thus it ionizes matter mostly with nucleus in collision, causing some displacement of the nuclei or in absorption, causing the formation of other isotopes and subsequent induced radiations of various types.

- **All elements have atoms with neutrons except for one:**

  A normal hydrogen (H) atom does not have any neutrons in its tiny nucleus. That tiny little atom (the tiniest of all) has only one electron and one proton. You can take away the electron and make an ion, but you can’t take away any neutrons.

- **Decay of the Neutrons:**

  Outside the nucleus, free neutrons are unstable and have a mean lifetime of $881.5 \pm 1.5s$ (about 14 minutes, 42 seconds).Free neutrons decay by emission of an electron and an electron antineutrino to become a proton, a process known as beta decay.

$$n^{0} \rightarrow p^{+} + e^{-} + \nu_{e}^{-} \tag{1.2.1}$$

Here neutrons in unstable nuclei can decay in the most common manner above. However,inside a nucleus, protons can also transform into a neutron via inverse beta decay. This transformation occurs by emission of an antielectron (also called positron) and an electron neutrino:

$$p^+ \rightarrow n^0 + e^+ + \nu_e \tag{1.2.2}$$

The transformation of a proton to a neutron inside of a nucleus is also possible through electron capture:

$$p^+ + e^- \rightarrow n^0 + \nu_e \tag{1.2.3}$$

- **Magnetic moment:**

It is of particular interest,as magnetic moments are created by the movement of electric charges. Since the neutron is a neutral particle,the magnetic moment is an indication of substructure, i.e. that the neutron is made of other, electrically charged particles (quarks). Even though the neutron is a neutral particle, the magnetic moment of a neutron is not zero because it is a composite particle containing three charged quarks.The neutron is considered to be composed of two down quarks with charge $\frac{-1}{3}e$ and one up quark with charge $\frac{+2}{3}e$ [3].

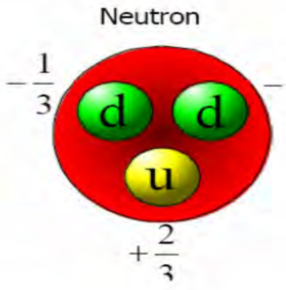

Figure 1.2: Composition of the neutron,(http://en.wikipedia.org/wiki/Neutrons)

In SI units, the neutron magnetic moment is approximately, $-9.6623640\times10^{-17}JT^{-1}$. The magnetic moment is negative which means that the neutron has a tendency to align antiparallel to a magnetic field rather than parallel to the field. Neutrons carry a magnetic moment and can be used to investigate magnetic materials.

- **Temperature of the neutron:**

  The kinetic energy, E, of the neutron is given by $\frac{mv^2}{2}$, which is conventionally related to temperature via the Boltzmann constant, $(K_B = 1.381 \times 10^{-23}JK^{-1})$, according to the equation: $E = \frac{mv^2}{2} = K_BT$. Taking room temperature as 20^0C, i.e. 293K, a velocity equal to $2200ms^{-1}$ is obtained for thermal neutrons.

- **Zero Net Charge:**

  The net electrostatic charge of a neutron is zero so that a moving neutron has very great penetrating power in materials consisting of charged particles; e.g., penetration through several inches of lead[3]. Since magnetic moment property depends upon moving charge, a zero net charge implies that positive and negative charges are paired. Empirical evidence shows that a neutron sometimes decays, producing an electron and proton simultaneously. Since the electron and proton have equal but opposite charge, a neutron consisting of one electron and one proton would have zero net charge.

1.3 Classification Of Neutrons Based On Their Energies

Neutrons are usually classified according to their energies or velocities because their interaction with matter is energy dependent.Some author classified neutrons based on their energy to three general categories (thermal,epithermal and resonance),while other classified the neutrons based on their energy to eight categories (slow, cold, thermal, epithermal, resonance, intermediate, high energy and ultra high energy neutrons)[2],[9]. The most common classification are listed below:-

- **Cold Neutrons**

  Cold neutrons have a temperature considerably lower than normal room temperature.These neutrons has got energy range between 0 to 0.025 ev

- **Thermal Neutrons**

  Thermal neutrons are so called because they have energies which are those that a particle has as a result of it existing a room temperatures. In other words, they only have the small energies associated with the random kinetic motion associated with room temperatures. They are those that have reached thermal equilibrium with their surroundings and has got energy 0.025 ev and also velocity around 2200m/sec. Since the kinetic energy, E, can be related to temperature via:

  $$E = \frac{1}{2}MV^2 = \frac{3}{2}K_BT \tag{1.3.1}$$

  the characteristic neutron temperature of a several-MeV neutron is several tens of millions of degrees Celsius.

- **Epithermal Neutrons**

  These are neutrons of kinetic energy greater than that of thermal agitation($E_n > 0.025ev$). The term is often restricted to energies just above thermal.

- **Slow Neutrons**

  Slow neutrons of kinetic energy less than some specified value. This value may vary over a wide range and depends on the application. In reactor physics, the value is frequently chosen to be 1 eV.

- **Resonance Neutrons**

  Resonance neutrons are,the energy of which corresponds to the resonance energy of a specified nuclide or element. These neutron energy ranges up to $300ev$.We call it resonance,because large number of resonance in neutron reaction were observed at these energies.

- **Intermediate Energy Neutrons**

  Neutrons of kinetic energy between the energies of slow and fast neutrons(1 ev to 100 kev) are called Intermediate energy neutrons. .

- **Fast Neutrons**

  Fast neutrons are free neutrons with a kinetic energy greater than some specified value ($\geq 0.1MeV$). This value may vary over a wide range. They are named fast neutrons to distinguish them from lower energy thermal neutrons, and they are produced in accelerators or nuclear fission.

- **Very Fast Neutrons**

  These are high energy neutrons and has got neutron energy in the range $10Mev < E < 50Mev$.

In general,Table 1.1 describe classification of neutrons based on their energies.

Table 1.1: Classification of neutrons on the basis of their energy

Ranges of neutron energy	Name
0-0.025	cold neutrons
0.025	Thermal neutrons
0.025-0.4ev	epithermal neutrons
0.5ev-1ev	Slow neutrons
1ev-300ev	Resonance neutrons
300ev-0.1Mev	Intermediate neutrons
0.1Mev-10Mev	Fast neutrons
10Mev-50Mev	Very fast neutrons
$> 50Mev$	Ultra fast neutrons

Chapter 2

NEUTRON INTERACTION WITH MATTER

Neutrons interact with matter in a different way from other types of radiation. Many types of reactions are possible when a neutron hits a nucleus. The probability of each type of reaction happening depends on the nucleus and is very sensitive to the energy of the neutron.

Since neutrons are neutral particles,they do not electrically interact with the atomic electrons, interacting directly with the nucleus. Thus, they present a high capability of penetration in most materials. Study of the neutron interaction with matter requires the knowledge of neutron energy spectrum. All neutrons are fast by birth and lose energy by colliding elastically with atoms in their environment and then after being slowed down to thermal energies they are captured by the nuclei of the absorbing medium [15].

So there are several types of neutron-matter interactions and each of them occurs with a certain probability. This probability depends on many factors and this topic is discussed later. The interaction of a neutron with matter is broadly classified as of two types:

1. Absorption and
2. Scattering

We here (in figure 2.1) consider the different reactions by which a neutron can interact with matter.

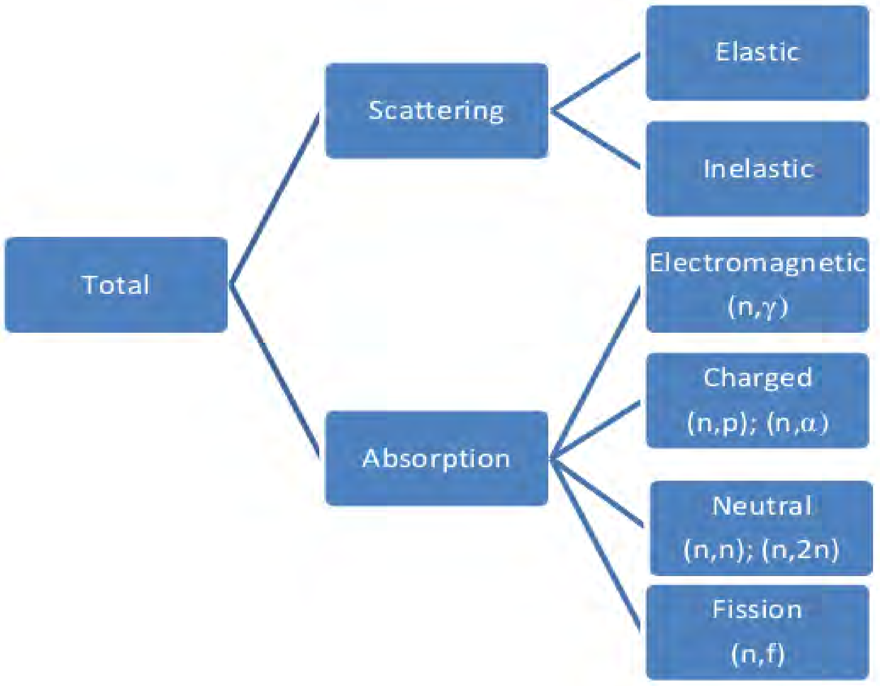

Figure 2.1: various catagories of neutron interaction [9]

2.1 Neutron absorption

During this reaction the incident neutron is absorbed in the target nucleus and another particle is released instead. Absorption leads to the disappearance of free neutrons as a result of a nuclear reaction with fission or the formation of a new nucleus and another particle such as protons,alpha particles and gamma photons.

2.1.1 Charged particle emission [(n,p) and (n,α)]

These are the reactions with energy thresholds in which the neutron causes the emission of charged particles (protons or other heavier particles) from the target nucleus.A charged particle reaction(as shown in figure 2.2) usually leads to emission of an α-particle or a proton from the nucleus.

Charged particle emission occur at high neutron energies [(n, α), (n,p) type]. Thus charged particle reactions are usually rare with slow neutrons.

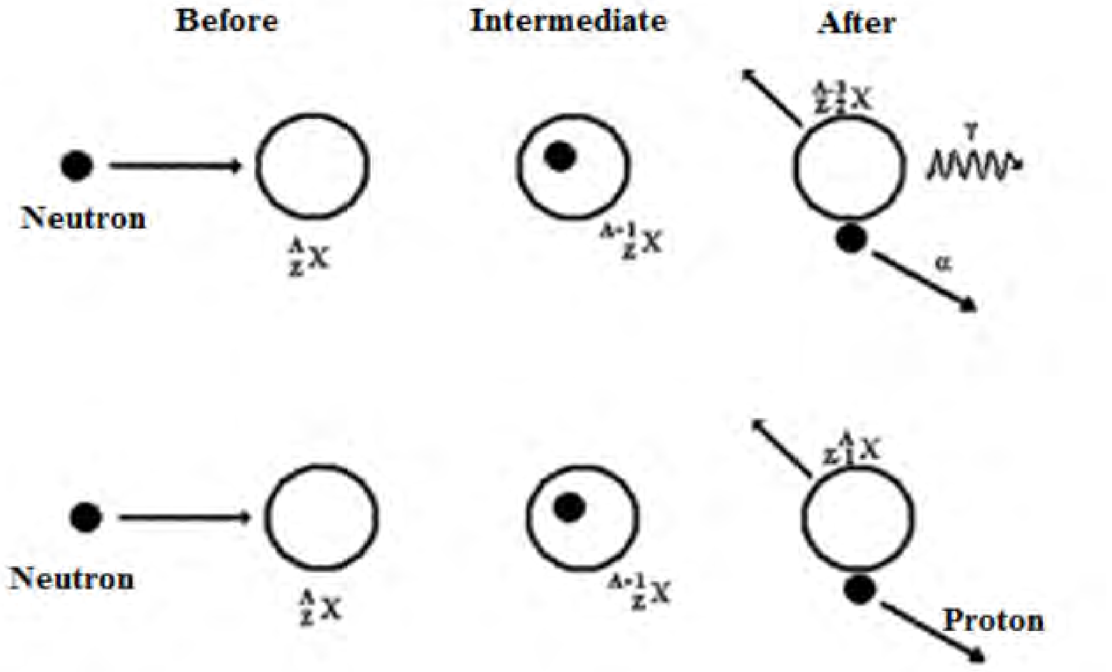

Figure 2.2: Schematics of charged particle emission.

For instance look at the reaction given below,which illustrate more about the above figure.

$$^{208}_{82}Pb + n \rightarrow (^{209}_{82}Pb)^{*} \rightarrow^{208}_{81} Tl + p$$

In this reaction Lead,$^{208}_{82}Pb$,captures a neutron and the product is radioactive and decays back to the ground state by emission of proton.Similarly the following reactions captures a neutron and emits a alpha particles.

$$^{10}_{5}B + n \rightarrow (^{11}_{5}B)^{*} \rightarrow^{7}_{3} Li + \alpha$$

$$^{6}_{3}Li + n \rightarrow (^{7}_{3}Li)^{*} \rightarrow^{3}_{1} H + \alpha$$

2.1.2 Fission(n,f)

Nuclear fission is a phenomenon in which a heavy nucleus, splits into two smaller nuclei, called the fission fragments, mostly of unequal masses, one often with nearly half the mass as the other, and rarely of equal masses. This reaction gives off a large amount of energy and emits two or more neutrons, and gamma rays. When a neutron hits a heavy nuclide like U-235, the neutron gets absorbed in the heavy nuclide that gets energetically agitated (or excited). If the new energy state of the heavy nuclide is sufficient for it to split, then it can split to cause fission. The neutrons produced in fission are fast. One example of (n,f) reaction is splitting of heavy nuclei by neutron is given below in figure 2.3 [9].

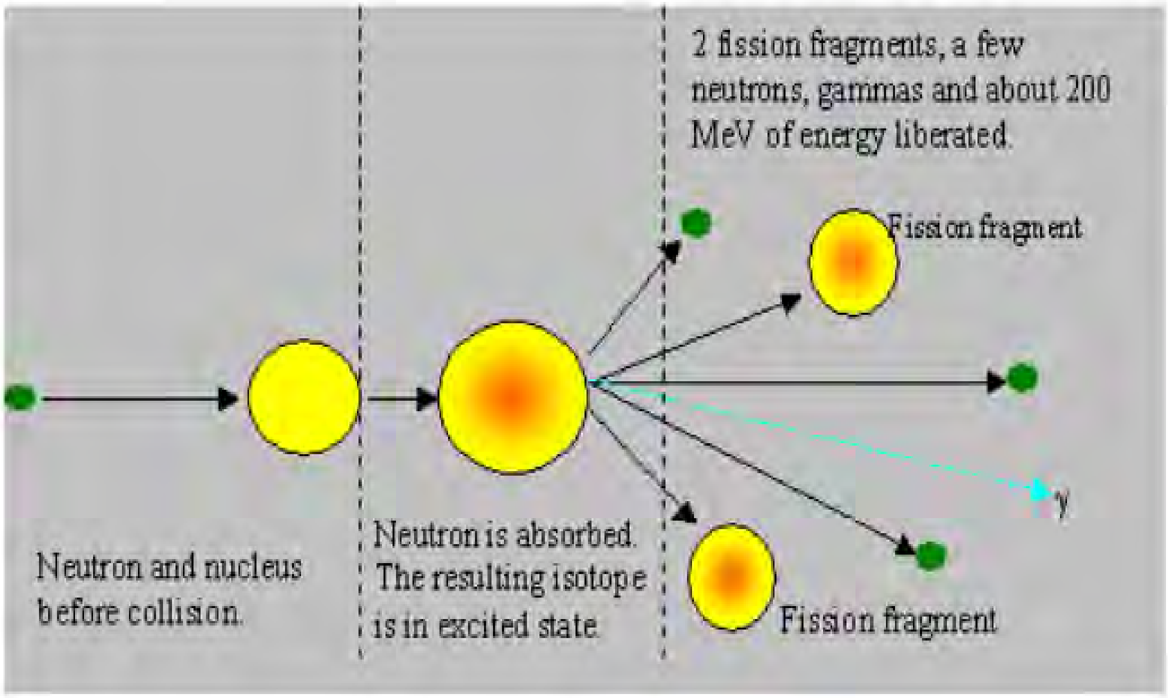

Figure 2.3: Neutron induced fission reaction (n,f) (courtesy:www.nuceng.caignaneutron-interactions).

2.1.3 Radiative Capture (n, γ)

Nuclear process in which a neutron is captured by the target nucleus and the excess energy emitted as radiation, is called radiative capture process. In these reaction neutron is absorbed by the target nucleus to form the next higher isotope (of mass A+1), in an excited state of energy. The new isotope de-excites by emitting gamma rays. The neutron is thus lost in this reaction. The (n, γ) reactions in which part of the energy released by the capture of the neutron is carried away by the emitted photon.

Neutron capture is often called radiative capture because gamma rays are mostly emitted in these reactions. Conditions for such reactions are especially favorable during slow neutron (with energy$< 1ev$) interaction with medium [9]. The process is of very great importance in the production of radio-isotopes.

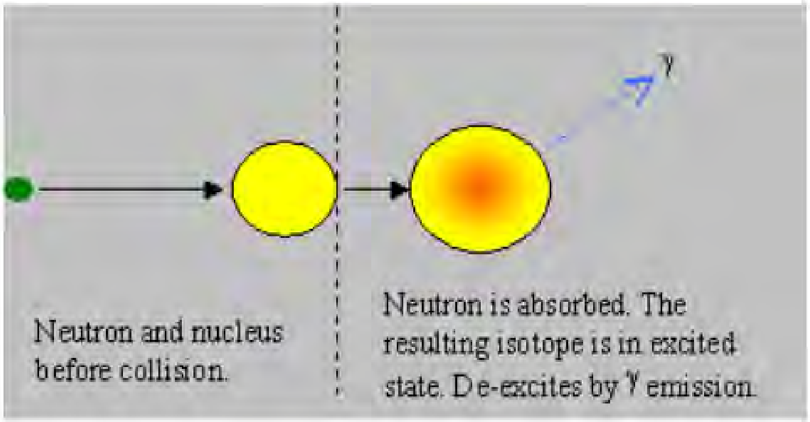

Figure 2.4: Radiative neutron capture (courtesy:www.nuceng.caignaneutron-interactions)

The radiative capture reaction (as shown above) can be more illustrated by the following reaction:

$$(Z, A) + n \rightarrow (Z, A+1)^* \rightarrow (Z, A+1) + \gamma \tag{2.1.1}$$

The compound nucleus formed here is having mass number increased by one from the original nucleus. The newly formed nucleus can be radioactive and will therefore decay by emitting one or several gamma rays.

2.2 Neutron scattering

The incident neutron bounces from the target nucleus and continues its journey through the matter. Scattering interactions result in the neutron changing energy or direction but cannot directly cause the disappearance of a free neutron. They can be elastic or inelastic[10].

$$(n,n)elastic :^{A} Z +^{1} n \rightarrow [^{A+1}Z]^{*} \rightarrow^{A} Z +^{1} n \tag{2.2.1}$$

$$(n,n')inelastic :^{A} Z +^{1} n \rightarrow [^{A+1}Z]^{*} \rightarrow [^{A}Z]^{*} +^{1} n \tag{2.2.2}$$

2.2.1 Elastic scattering (n,n)

When neutron and the nuclide collide they rebound with speeds different from the original speeds, such that the total kinetic energy before and after the collision remains the same. If the nucleus is stationary before collision, it will gain energy from the neutron and start moving, and the neutron gets slowed down due to loss of kinetic energy. However,the residual nucleus is not excited but is in its ground state. In this collision the nucleus does not suffer any structural change and there is no energy transfer for generation of radiation,the total kinetic energy of the neutron and nucleus is unchanged by the interaction[9].

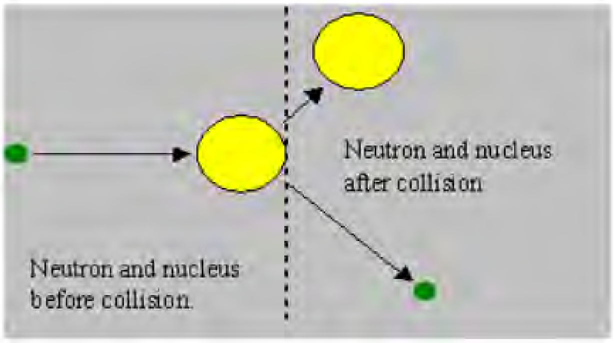

Figure 2.5: Elastic collision(courtesy:www.nuceng.caignaneutron-interactions)

2.2.2 Inelastic scattering (n, n')

Inelastic scattering is similar to elastic scattering except that the nucleus undergoes an internal rearrangement into an excited state from which it eventually releases radiation[10]. In this case a part of kinetic energy of the incident neutron is given off in the form of one or more gammas. This process always takes place through the formation of compound nucleus.

In order for a neutron to undergo inelastic scattering with a nucleus, its incident energy must to be sufficient to place the target nucleus in an excited state.This scattering proceeds through two steps: In inelastic scattering, the incident neutron is absorbed by the target nucleus,forming a compound nucleus. The compound nucleus will then emit a neutron of lower kinetic energy, which leaves the original nucleus in an excited state, the nucleus then usually, by one or more gamma emission, emit this excess energy to reach its ground state. In inelastic scatter the neutron is absorbed and then re-emitted. The nucleus absorbs some energy internally and is left in an excited state[15]. Figure 2.6 (below) shows this process of scattering:

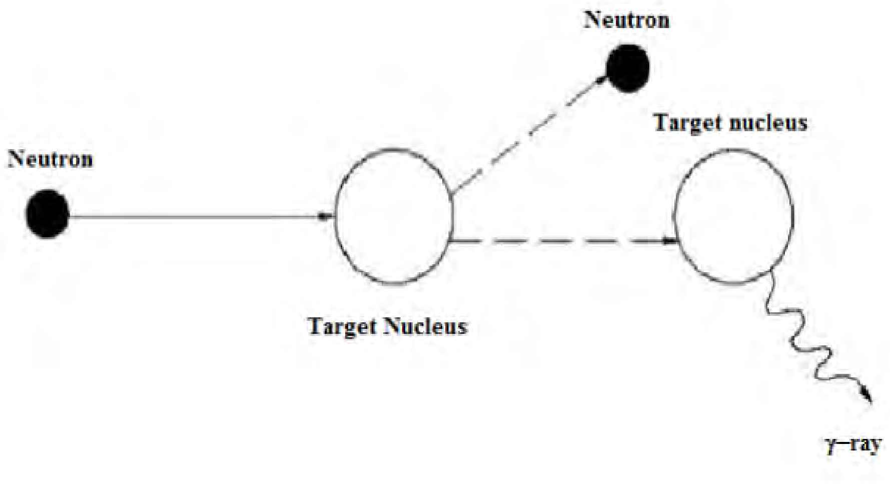

Figure 2.6: Inelastic neutron scattering from the target [9]

2.3 Neutron Cross section

All the described neutrons interactions (above) have a certain probability to happen. The probability of a particular event occurring between a nucleus and a neutron is expressed by the concept of cross section.

2.3.1 Microscopic Cross Sections

The probability of a particular interaction occurring between a neutron and a nucleus is called the microscopic cross section (σ) of the nucleus for the particular interaction. Because the microscopic cross section has definition of an area, it is expressed in unit of area, or square centimeters. A square centimeter is large compared to the effective area of a nucleus, hence it is expressed in a smaller unit of area called a barn. One barn is 10^{-24} cm^2 [2][11]. There are different types of cross sections and these different cross sections may be added to give a total cross section. The nomenclature for different cross sections is given below with the different types of interactions[14]:

σ_e = Elastic scattering cross section
σ_i = Inelastic scattering cross section
$\sigma_{n,\gamma}$ = Radiative capture cross section
σ_a = Absorption cross section
σ_f = Fission cross section.

When these are combined they are added together, so that the scattering cross-section includes both elastic and inelastic scattering and the absorption cross-section includes both radiative capture and fission cross section. For a particular isotope all the individual microscopic cross sections can be added to give the total microscopic cross section[10].

$$\sigma_{total} = \sigma_e + \sigma_i + \sigma_a + ... \tag{2.3.1}$$

2.3.2 Macroscopic Cross Sections

The macroscopic cross section Σ is the cross section density in a material. It is defined as the number of nuclei per unit volume N multiplied by the microscopic cross section σ.

$$\Sigma = N\sigma \tag{2.3.2}$$

For a single isotope the macroscopic cross section can be determined from the above equation. This gives the effective cross section density in a pure material and indicates the probability of a neutron interaction within that material. If there is a homogeneous mixture of different isotopes the cross section density can be calculated separately for each and then added to give the total macroscopic cross section[10].

$$\Sigma = N_a\sigma_a + N_b\sigma_b + N_c\sigma_c... \tag{2.3.3}$$

Note that N is the number of nuclei or atoms of each element per unit volume in the material.

2.4 Attenuation of neutrons

All neutrons, at the time of their birth, are fast. Those fast neutrons lose energy by colliding elastically with atoms in their environment, and then, after being slowed down to thermal or near thermal energies, they are captured by nuclei of the absorbing material. When absorbers are placed in a collimated beam of neutrons and the transmitted neutron intensity is measured,it is found that neutrons are removed exponentially from the beam. This happens when a beam of neutrons impinges upon a solid body, the neutrons interact with nuclei within the body. Those not interacting continue through the body. As the beam progresses through the body more and more interactions occur and less and less neutrons continue on through the material. The beam of neutrons diminishes in intensity and is attenuated by the material. The decrease in intensity dI over any section of material is proportional to the neutron beam intensity I, microscopic cross-section of the material σ, number density of nuclei and the thickness of the material dx [14]:

$$dI = -\sigma I N dx \tag{2.4.1}$$

If the macroscopic cross section is used this becomes;$dI = -I\Sigma dx$,where $\Sigma = N\sigma$ The solution to this differential equation,or the removal of neutrons from the beam is thus given by:

$$I = I_o e^{-\Sigma x} = I_o e^{-\sigma N x} \tag{2.4.2}$$

where I_o = Initial intensity of incident neutrons, I=Transmitted intensity of neutrons after passing through x,thickness of the target.

Chapter 3

NEUTRON PRODUCTION

Neutrons are found bounded inside a nucleus of an atom, almost all elements in periodic table contains at least one neutron bounded inside their nucleus except ordinary hydrogen atom which contains only one proton inside its nucleus. If one needs neutrons of different energy for any purpose he should extract neutrons from the nucleus of certain element by imparting energy to it, the minimum energy needed by a nucleus to emit one neutron is nearly equal to the binding energy of a neutron, approximately around 7Mev.[9]

Free neutrons do not occur naturally, so they have to be created artificially. As neutral particles with an average lifetime of 15 minutes they cannot be stored or accelerated like charged particles. Therefore neutrons have to be created with energies higher or equal of the intended treatment energy. The use of radioactive sources and certain target substances may yield neutrons by either the (α, n) or (γ, n) reaction. Accelerator produces neutrons when high-energy particles strike suitable targets.Neutrons also result from the fission process in a reactor. So neutrons, users have various primary sources.The most common neutron sources are mentioned in the following survey[12].

3.1 Radioactive Sources

Neutrons are produced when radioactive particles impinge upon any of several low atomic weight isotopes including isotopes of lithium, beryllium, carbon and oxygen. There are several types of radioactive neutron sources, differentiated both by the nature of the target material and of the radioactive nuclide producing the bombarding radiation. These radioactive sources, which have been found useful, are discussed below. In general it may be said that neutron sources, which depend up on radioactive preparation for the bombarding radiation, are limited in the rate of neutron emission, which can be conveniently achieved. Therefore the radioactive sources and certain target substances may yield neutrons by either the (α, n) or (γ, n) reaction, which have been used in the past, have an order of neutron emission not greatly exceeding 10^7 neutrons in one second[9].

3.1.1 (α, n) Neutron Sources

Radioactive (α, n) sources have historical significance in connection with the discovery of neutrons and are most useful of the radioactive sources. There are several radioactive alpha-sources of various half life and energy. This nuclear reaction can be used to construct a neutron source by intermixing a radioisotope that emits alpha particles such as radium or polonium with a low atomic weight isotope,usually in the form of a mixture of powders of the two materials. Po,Ra,Am,Cf,Th (heavy elements) are neutral alpha emitter. Alpha neutron sources are the most commonly encountered type of neutron source. The source strength is specified by the activity of the alpha emitter[11]. It should be noted though, that isotopes with too short a half life will become too impractical to produce and use effectively as an (α, n) neutron source. Therefore, a reasonable half-life for α emitters, for use in a neutron source, should be on the order of 1 to 25,000 years. The useful lifetime for these types of sources is highly variable,depending upon the half-life of the radioisotope that emits the alpha particles. Several light nuclei are prone to undergoing the (α, n) reaction. The nuclei are referred to as targets and are listed in Table 3.1, along with the reaction energy (Q value), threshold energy for the reaction and relative neutron yield and neutron energy for a 5.5 MeV α particle.[14]

Table 3.1: Different targets along with the reaction energy (Q value),threshold energy for the reaction and relative neutron yield

Target	Q (Mev)	Threshold energy (Mev)	Mean E_n, for $E_\alpha = 5.5Mev$	Yield (n/$10^6\alpha$)
^7Li	-2.79	4.382	0.5883	3.156
^9Be	5.702	exothermic	5.005	80.073
^{10}B	1.06	exothermic	2.243	5.72
^{11}B	0.157	exothermic	2.93	23.724
^{13}C	2.25	exothermic	4.72	9.9904
^{17}O	0.587	exothermic	2.523	0.152
^{18}O	-0.697	0.852	2.374	0.33
^{19}F	-1.97	2.361	1.304	0.106

As shown in Table 3:1, the greatest neutron yield is achieved when beryllium is used as a target material in the (α, n) reaction. Because of the high yield of neutron from beryllium, this element has been used almost exclusively as the target material in (α, n) radioactive neutron sources. Common beryllium target (α, n) sources are [11]:

a) Polonium - Beryllium
b) Radium - Beryllium
c) Plutonium - Beryllium
d) Americium - Beryllium

a) Polonium - Beryllium

The Polonium - Beryllium (Po- Be) neutron source has historical interest because it was used in the discovery of neutron. This source emits gamma rays of very low intensity that a practical advantage possessed by few other radioactive neutron sources. On the other hand, Po-Be neutron source has relatively rapid rate of decay. ^{210}Po, used in this neutron source, has a half-life of approximately 140 days. The maximum α energy from polonium is 5.3 MeV.The (α, n) reaction by which alpha particles release neutrons from beryllium can be represented by:

$$^{9}_{4}Be +^{4}_{2} He \rightarrow^{12}_{6} C +^{1}_{0} n + 5.7Mev \tag{3.1.1}$$

Hence the reaction is exotermic.

b) Radium-Beryllium

Prior to the development and general availability of accelerators, the Ra-Be, (α, n) sources were the most common way to generate neutrons. This has been performed using a mixture of fine beryllium powder and radium bromide as a source of neutrons. Part of this popularity is based on the case with which large preparation of radium could be obtained and the long half- life of radium. The half- life is about 1690 years insured that the rate of emission of neutrons would be essentially constant with time. Ra-Be sources have the disadvantage of emitting an intense and penetrating gamma radiation. The gamma rays are hazard to health and also produce objectionable effects in some type of detectors of neutrons.

c) Plutonium - Beryllium

The conveniently available plutonium isotope is ^{239}Pu, which emits 5.1 MeV alpha energy particles. The half-life is about 2.3×10^4 Years. The gamma rays emitted in the radioactive decay of ^{239}Pu are weak and of low energy. Therefore Pu-Be neutron sources have the advantage over Ra-Be sources of long half-life and the favorable characteristic of Po-Be sources of low intensity of gamma radiation. The neutron yield is somewhat lower for Pu-Be sources than from Ra-Be sources.

D) Americium - Beryllium

This (α, n) sources, ^{241}Am, has a half-life of about 470 years.Although this isotope decays by emitting alpha particles of about 5.4 MeV, these particles are followed by gamma rays in the 40 to 60 KeV regions in the majority of the disintegrations. This gamma ray emission makes americium appear less satisfactory than plutonium for the preparation of neutron sources.

In general table 3:2 listed many common radionuclides used in (α, n) neutron sources today, along with their half-lives,common decay energies and thick target yield with beryllium in $(n/10^6\alpha)$[14].

Table 3.2: common radionuclides used in (α, n) neutron sources today, along with their half-lives,common decay energies and thick target yield with beryllium

Sources	$T_{1/2}$	Most common E_α (Mev)	Yield (n/$10^6\alpha$)
$^{239}Pu - Be$	24110yrs	5.156	57.2
$^{210}Po - Be$	138.38d	5.304	63.7
$^{241}Am - Be$	432.2 yr	5.499	72.1
$^{238}Pu - Be$	87.7 yr	5.156	57.2
$^{238}Cm - Be$	18.1 yr	5.805	1005.3
$^{244}Cm - Be$	162.8 d	6.113	88.1
$^{226}Ra - Be$	1600 yr	4.874,5.490,6.002,7.687,5.304	521.6
$^{228}Ra - Be$	5.75 yr	5.422,5.686,6.288,6.779,8.784	707.2
$^{228}Th - Be$	1.911 yr	same as ^{228}Ra	707.2

3.1.2 (γ, n) Neutron Production

Radioisotope gamma-ray emitters can be used to produce neutrons when combined with an appropriate target material.Some radioactive γ- emitters are used as the parent γ- sources and some elements like ^{9}Be and deuterium oxide (D_2O) can be used as target material. In some nuclei, gamma radiation from radioactive isotopes with an energy exceeding the neutron binding energy of a nucleus can eject a neutron.In this process gamma radiations from ^{24}Na, ^{226}Ra, ^{124}Sb, ^{72}Ga and ^{140}La are bombarding with ^{9}Be and ^{2}H,to give neutrons. The minimum energy needed by the gamma radiation to eject a neutron from a given nuclei is called threshold energy. Beryllium and Deuteron have threshold energy about 1.666Mev and 2.225Mev respectively, which have smaller threshold value.

For instance,^{9}Be has a treshold energy for (γ, n) reaction is about 1.66 Mev.This energy of 1.66 Mev or more can initiate (γ, n) reaction in ^{9}Be target and we can get neutrons sources of nearly monochromatic wave length[9]. Half life of these neutron sources will depend upon the half life parent γ-ray emitter.Strength or intensity will depend upon the strength of γ-emitter.

Similarly D_2O can also be used as the target and breaking of deuteron by γ-ray. Gamma energy, E_γ more than deuteron threshold energy, E_{Th} where $E_{Th} = 2.226 Mev$ can disintegrate deuterons to produce neutrons[13].So neutron sources can be made using D_2O as a target and γ-emitter having $E_\gamma \gg 2.226 Mev$ as the gamma sources. In contrast to (α, n) sources,which emit neutrons with a continuous energy spectrum, monoenergetic photoneutrons can be obtained by selecting a radioactive isotope that emits a single photon. The resulting photoneutron sources are based on the absorption of a gamma-ray photon to allow the emission of a free neutron. Here are some of the examples;

$$\gamma +^9 Be \rightarrow^8 Be +^1_0 n + Q \tag{3.1.2}$$

$$\gamma +^2_1 H \rightarrow^1_1 H +^1_0 n + Q \tag{3.1.3}$$

If the energy of the incident $\gamma-$radiation is sufficient to overcome the neutron binding energy,a neutron with well-defined energy is released. Here table 3.3 shows properties of some of photoneutron sources.

Table 3.3: (Cierjacks, 1983) some common photoneutron sources and their properties

γ Sources	$T_{1/2}$	E_γ (Mev)	Target	E_n (Kev)	Yield (n/$10^{10}Bq$)
^{24}Na	15 hr	2.7541	Be	967	340000
^{24}Na		2.7541	D	263	330000
^{28}Al	2.24 m	1.7787	Be	101	32600
^{38}Cl	37.3 m	2.1676	Be	446	43100
^{56}Mn	2.58 hr	1.8107	Be	129	91500
		2.1131	Be	98	91500
		2.9598	Be	1149	91500
		2.9598	D	365	162
^{72}Ga	14.1 m	1.8611	Be	174	64900
		2.2016	Be	476	64900
		2.5077	Be	748	64900
		2.5077	D	140	25100
^{76}As	26.3 hr	1.7877	Be	109	3050
		2.0963	Be	383	3050
^{88}Y	107 d	1.8361	Be	152	229000
		2.734	Be	949	229000
		2.734	D	253	160
^{124}Sb	60.2 d	1.691	Be	23	210000
^{140}La	40.3 hr	2.5217	Be	760	10200
		2.5217	D	147	6600

Those radioisotopes,which decay with gamma ray greater than the threshold of these nuclei, co-located with Beryllium and Deuteron, used as neutron(γ, n) source.

3.1.3 Spontaneous Fission Source

In this source,certain transuranic heavy nuclide undergo spontaneous fission at a rate sufficient to give a useful neutron source. Each such fission may produce several neutron as well as beta and gamma rays. The most commonly used spontaneous fission neutron source is Californium-252.It undergos an alpha decay with 97 percent and half-life 2.65 year[8]. When purchased new a typical Cf-252 neutron sources emit between 1×10^7 to 1×10^9 neutrons per second but, with a half life of 2.6 years, this neutron output rate drops to half of this original value in 2.6 years.

3.2 Reactor as a neutron sources

Nuclear reactors are clearly the largest and most prolific sources of neutrons. However, their size, complexity, and cost have limited their industrial applications for purposes other than electricity generation [6]. Nuclear fission which takes place within the reactors produce very large quantities of neutrons and can be used for a Variety of purposes including power generation and experiments. A nuclear reactor is a source of products of fission process,such as, energy,neutron and some useful radioactive isotopes. The fission reaction which takes place in the reactors using slow or thermal neutrons having energy 0.0253ev and velocity about 2200m/s[2].

U,Th and Pu are fissionable materials, with radio-isotopes $^{233}U,^{235}U,^{238}U,^{232}Th$, $^{239}Pu,^{241}Pu$. Fission generally refers to the splitting. In case of nuclear or atomic fission, it is division or splitting of atom or nucleus into sub-atoms or sub-nuclei. The generated atoms or nuclei are known as daughter nuclei or daughter atoms. And the original matter is called the parent. Fission is always followed by release of large amount of energy. The splitting of a uranium or a plutonium nucleus in a nuclear reactor is accompanied by the emission of several neutrons. These fission neutrons have a wide range of energies and have a mean value of ≈ 2 MeV[5].

One of the most important nuclear reactions is that of uranium 235 which is initiated when a neutron of enough velocity collides with the nucleus of uranium 235. This collision produces uranium 236 which immediately splits into two lighter elements i.e. krypton-90 and barium-144. This event also releases two neutrons and energy. The neutrons produced are capable of producing more nuclear fission events if they encounter a uranium 235 nucleus [see also section 2.1.2]. Nuclear fission equation of Uranium 235 is given below:

$$ {}_0^1n +_{92} U^{235} \rightarrow ({}_{92}U^{236})^* \rightarrow_{36} Kr^{90} +_{56} Ba^{144} + 2n \tag{3.2.1} $$

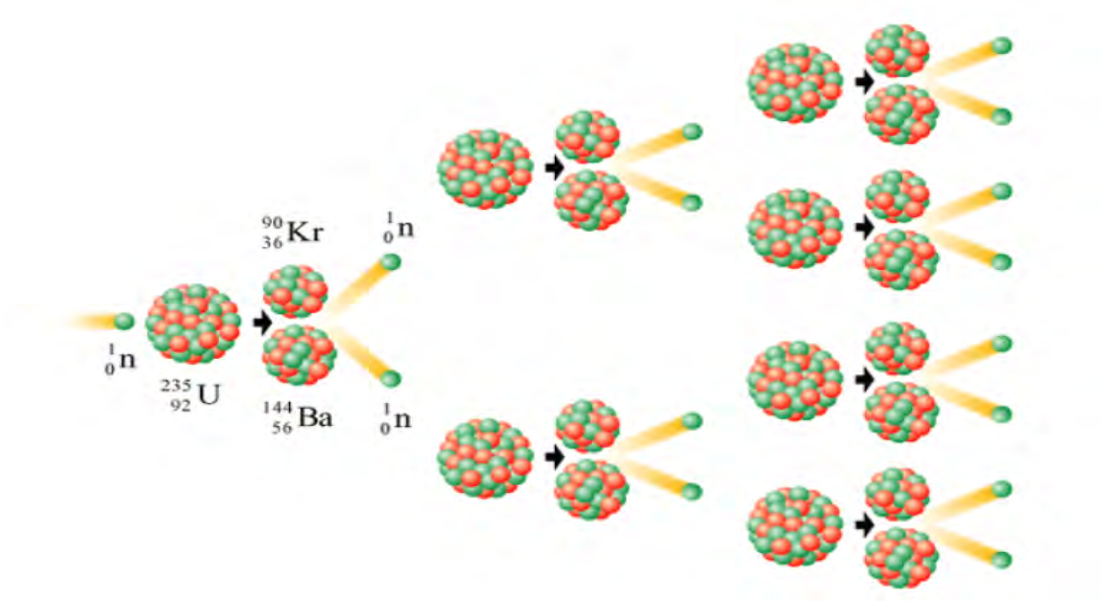

Figure 3.1: Nuclear fission process

This neutron reaction splits the target nucleus into two lighter nuclei and an average of 2 to 3 neutrons is emitted in case of ${}^{235}U$ by thermal neutron bombardment while, the following averages are for the Pu isotopes that appear during reactor operation [13]:

For $Pu^{239} \rightarrow n = 2.89$

For $Pu^{241} \rightarrow n = 2.93$

3.3 Accelerator Source

In the early years, reactors were the strongest sources for neutrons of all energies in the MeV range and below. This is no longer true,because these neutron sources can produce energies in MeV range and above. Accelerator neutron sources are neutron sources or devices which used proton and deuteron as a projectile and materials made from light atoms, such as, deuterium, tritium, lithium, and berryllium are taken as a target material in order to emit neutrons. These types of neutron sources are characterized by higher neutron brightness and higher peak intensity than reactor-based sources. They are also more efficient and more environmentally friendly than reactor-based sources [7].

3.3.1 The (d, n) reaction as source of neutron

The (d, n) reactions are the most popular reactions as a source of neutrons in accelerators.These are neutron source devices which contain compact linear accelerators and that produce neutrons by fusing isotopes of hydrogen together. Accelerators with hydrogen (H);deuterium (D) or tritium (T) ion sources may be used to produce neutron using targets of deuterium,tritium,lithium, beryllium and other low-z metals. Typically these accelerators operate with a voltage in the range of 1 Mev and above. The fusion reactions take place in these devices by accelerating either deuterium, tritium, or a mixture of these two isotopes into a metal target which also contains deuterium,tritium or a mixture of these isotopes[13].

Fusion of deuterium atoms (D + D) results in the formation of a ${}^3He$ ion and a neutron with a kinetic energy of approximately 2.5 MeV. Fusion of a deuterium and a tritium atom (D + T) also results in the formation of a ${}^4He$ ion and a neutron with a kinetic energy of approximately 14.1 MeV.

$$ {}^2_1H +^3_1 H \rightarrow^1_0 n +^4_2 He \qquad\qquad Q = 17.586 Mev \tag{3.3.1}$$

The ${}^3H(d,n)^4He$ reaction is outstanding, among the (d, n) reactions which have been used for generating mono-energetic neutrons, for its high positive value of Q. Similar devices are also available that are based on the Deuterium-Deuterium fusion reaction.The neutrons emitted in that reaction are mono-energetic at 2.5 MeV.

$$ {}^2_1H +^2_1 H \rightarrow^3_2 He +^1_0 n \qquad Q = 3.270 Mev \tag{3.3.2}$$

The D-D sources have significantly lower neutron output than the D-T type, which limits their use for different application. Both types of accelerator sources have similar problems of cost and maintenance. So in general accelerated deuteron can be used as projectile and $D_2O,^3H,^7Li,^9Be$ as a target, to produce neutrons. These reactions are used to produce neutrons of about 12 Mev to 18 Mev [2].

Here are some of the (d,n) reaction examples that produce neutrons:

${}^2H(d,n)^3He$	Q=+3.269 Mev	${}^2_1H +^2_1 H \rightarrow^3_2 He +^1_0 n$
${}^3H(d,n)^4He$	Q=17.6 Mev	${}^3_1H +^2_1 H \rightarrow^4_2 He +^1_0 n$
${}^7Li(d,n)^8Be$	Q=15.03 Mev	${}^7_3Li +^2_1 H \rightarrow^8_4 Be +^1_0 n$
${}^9Be(d,n)^{10}B$	Q=4.36 Mev	${}^9_4Be +^2_1 H \rightarrow^{10}_5 B +^1_0 n$

3.3.2 The (p, n) reaction as source of neutron

The (p, n) reaction has been popular reaction as a source of neutrons in accelerators. For instance in the ^3H (p, n) ^3He reaction,tritium is frequently used to produce neutrons. One reaction in which tritium may be used to generate neutrons is;[2]

$$^3_1H +^1_1 H \rightarrow^3_2 He +^1_0 n \tag{3.3.3}$$

Bombardment of tritium requires that it be in a form of suitable as a target. They must also be in a position to permit neutrons to be accepted at appropriate angles when mono energetic neutrons of special energy are needed. Although targets of low atomic number in the (p, n) reaction have been more popular in the past for the generation of neutrons, targets of higher atomic number have called attention for the production of mono-energetic neutrons in the kilovolt region of energies.[9]

Neutrons are generated through a variety of induced nuclear reactions like (p,n), (d,n), (t,n) and (α, n). In general the following table tells us,how different reaction produce neutrons [14].

Table 3.4: neutron producing reaction with their respective Q value

Reactions producing neutron	Q value (Mev)
$^3H(d,n)^3He$	+3.266
$^3H(p,n)^3He$	-0.764
$^3H(d,n)^4He$	+17.586
$^9Be(\alpha,n)^{12}C$	+5.708
$^{12}C(d,n)^{13}N$	-0.281
$^{13}C(\alpha,n)^{16}O$	2.201
$^7Li(p,n)^7Be$	-1.646

3.3.3 Areas of application

The neutron plays an important role in many nuclear reactions. For example, neutron capture often results in neutron activation, inducing radioactivity. In particular, knowledge of neutrons and their behavior has been important in the development of nuclear reactors and nuclear weapons. The fissioning of elements like uranium-235 and plutonium-239 is caused by their absorption of neutrons [7].

Nuclear reactors are clearly the largest and most prolific sources of neutrons. However, their size, complexity, and cost have limited their industrial applications for purposes other than electricity generation.In contrast, radioisotope neutron sources are used in a myriad of industrial applications, including petroleum exploration. In case of accelerators,positive particle beams from these accelerators can be used directly for the study of radiation effects in materials, to produce X-rays, or to generate intense light. Accelerators are used in medicine for producing intense X-ray beams for cancer treatment, or charged particle beams for similar purposes.

Because fast neutrons have a large effective range of penetration in most materials several tens of centimeters neutron analysis of bulk materials has significant advantages over certain laboratory techniques. This is particularly true where sample collection and preparation are a problem, as when samples are difficult to obtain or are not representative. Neutron-generator based systems typically run both fast and thermal neutron activation analyses to measure the elemental content of the major constituents in the bulk material.

Several national laboratories,universities,and private companies are investigating the development of neutron generator based systems for detecting high explosives, chemical weapons, and nuclear materials in a variety of objects. The goals of these organization include developing sensor systems for border security,airline-cargo inspection, and first response in the investigation of unknown packages.

Another application of neutron generators is in the measurement of body composition.

This is useful for evaluating the health of individuals with respect to obesity, aging, cardiovascular disease, and the amount of energy stored in body fat, as well as for assessing the nutritional effectiveness of different diets. So neutron-based research has enlarged our capabilities in certain fields.

Chapter 4

Conclusion

Since the existance of neutrons by chadwik,studies have shown that neutrons are produced through a variety of way. But here in these work,we only managed to see three different ways of production of neutrons. Those are through radioisotope source,nuclear reactor and accelerators driven neutron productions.

The use of radioactive sources and certain target substances may yield neutrons by either the (α,n) or (γ,n) reaction.Accelerator produces neutrons when high-energy particles strike suitable targets.Neutrons also result from the fission process in a reactor.So those produced neutrons has got many application including medical,industrial,agricultural ,quality control systems, exploration of natural resources, science and engineering applications.

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Declaration

This Project is my original work, has not been presented for a degree in any other University and and that all the sources I have used have been indicated and acknowledged by complete references.

Name: AWEL ABDELA HUSEN

Signature:

Place and time of submission: Addis Ababa University,June 2013

This Project has been submitted for examination with my approval as University advisor.

Name: Prof.A.K.CHAUBEY

Signature: