Nuclear Chemistry

Introduction

Chemical reactions take place as a result of changes in electronic configurations in the atoms but nuclei of the reactants remain unaffected in these transformations. It was observed in the beginning of the 19th century that certain chemical transformations (spontaneous or induced) are accompanied by altering the composition of the nuclei of the reactants in the atoms. Study of these changes gave birth to a new branch of chemistry known as Nuclear Chemistry. *Hence nuclear chemistry is the study of properties, composition and reactions of the atomic nuclei*.

4.1 Radioactivity

Radioactivity, Radioactive decay, or nuclear decay is the phenomenon by which a nucleus of an unstable atom loses energy by emitting particles of ionizing radiation. A material that spontaneously emits radiations like alpha particles, beta particles, and gamma rays, is called radioactive substance. Radioactive material may be element or compound. It has been claimed that radioactivity was discovered by Abel Niepce de Saint-Victor in 1857 but it was forgotten until 1906 when French scientist Henri Becquerel, rediscovered it while working on phosphorescent materials. Radioactivity may be natural or induced (artificial).

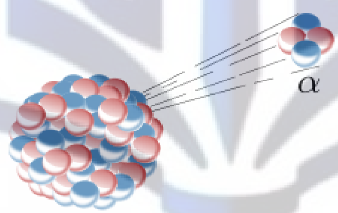

Figure 4.1: Emission of α-particles during natural radioactivity

4.1.1 Natural Radioactivity

Spontaneous emission of particles of ionizing radiations by a radioactive substance is called natural radioactivity. Rutherford and Soddy suggested that radioactivity involves decomposition of its nuclei into other elements and spontaneous emission of alpha, beta and gamma rays. These radioactive nuclei are called radionuclides and the atoms containing them are called radio isotopes. Some atoms are unstable and get stability by emission of particles or electromagnetic radiations.

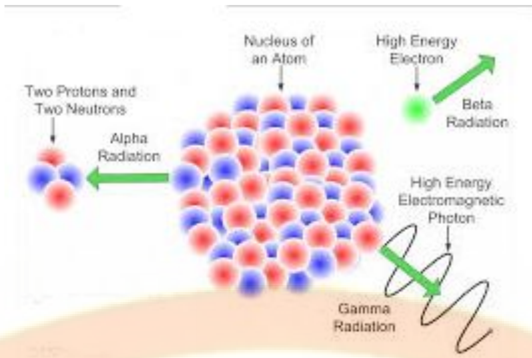

Figure 4.2: Three types of radiations emitted by a radioactive substance

Uranium-238 emits alpha decay in an attempt to get stability.

$$_{92}U^{238} \longrightarrow \; _{90}Th^{234} + {_2}He^4 \text{ (α-particles)}$$

Iodine-131 is an example of a radioactive isotope that undergoes beta emission to gain stability.

$$_{53}I^{131} \longrightarrow \; _{54}Xe^{131} + \text{ ß-particles}$$

It should be noted that atomic number increases in ß-decay. Beta emission results in the conversion of a neutron ($_0n^1$) to a proton ($_1p^1$). The electron comes from the neutron not from the electron cloud.

$$_0n^1 \longrightarrow (_1p^1)$$

> In a nuclear equation, the sum of atomic number and mass number of the reactants is equal to the sum of theatomic number and mass number of the product.

Radioactivity is a nuclear property and does not depend on the physical state or combination of matter. For example uranium will have the same radioactivity in elemental, combined or solution form.

4.1.2 Artificial Radioactivity

Artificial radioactivity or induced radioactivity occurs when a stable material is converted into radioactive material by exposure to specific radiations. The induced radioactivity was discovered by Irène Curie and F. Joliot in 1934. These reactions occur when stable isotopes are bombarded with particles such as neutrons. The new elements with atomic numbers greater than 92 have been artificially made. They are called the transuranium elements. When lighter elements such as boron and aluminium are bombarded with α-particles, the continuous emission of radioactive radiations takes place. The phenomenon is due to the emission of a particle carrying one unit positive charge with mass equal to that of an electron. Neutron activation is the main form of induced radioactivity which occurs when free neutrons are captured by nuclei. This new heavier isotope can be stable or unstable (radioactive) depending on the chemical element involved. Because free neutrons disintegrate within minutes outside of an atomic nucleus, neutron radiation can be obtained only from nuclear disintegrations, nuclear reactions, and high-energy reactions (such as in cosmic radiation showers or particle accelerator collisions). Neutrons that have been slowed down through a neutron moderator (thermal neutrons) are more likely to be captured by nuclei than fast neutrons. A less common form involves removing a neutron via photodisintegration. In this reaction, a high energy photon (gamma ray) strikes a nucleus with energy greater than the binding energy of the atom, releasing a neutron.

Not all nuclei of heavy elements are disintegrated spontaneously through nuclear reactions. These reactions occur when stable isotopes are bombarded with radioactive particles such as neutrons. Resultantly, nuclear reaction occurs which is termed as artificial radioactivity. For example, an isotope of aluminium, ${}^{27}_{13}\mathrm{Al}$, which is non-radioactive, when bombarded with alpha particle, it is converted into ${}^{30}_{15}\mathrm{P}$ with the emission of a neutron ${}^{1}_{0}\mathrm{n}$.

$$ {}^{27}_{13}\mathrm{Al} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{30}_{15}\mathrm{P} + {}^{1}_{0}\mathrm{n} $$

This type of radioactivity is called as artificial or induced radioactivity. The isotope of phosphorus ${}^{30}_{15}\mathrm{P}$ is further disintegrated and converted into stable isotope of silicon ${}^{30}_{14}\mathrm{Si}$ with the emission of positron, ${}^{0}_{+1}\mathrm{e}$.

$$ {}^{30}_{15}\mathrm{P} \longrightarrow {}^{30}_{14}\mathrm{Si} + {}^{0}_{+1}\mathrm{e} $$

Some more examples of artificial radioactivity are given here.

i) Conversion of stable isotope of boron (${}^{10}_{5}\mathrm{B}$) into radioactive isotope of carbon (${}^{13}_{6}\mathrm{C}$).

$$ {}^{10}_{5}\mathrm{B} + {}^{4}_{2}\mathrm{He} \longrightarrow {}^{13}_{7}\mathrm{N} + {}^{1}_{0}\mathrm{n} $$

$$ {}^{13}_{7}\mathrm{N} \longrightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{+1}\mathrm{e} $$

ii) Conversion of stable isotope of carbon (${}^{12}_{6}\mathrm{C}$) into radioactive isotope of carbon (${}^{13}_{6}\mathrm{C}$).

$$^{12}_{6}C + ^{1}_{1}H \longrightarrow ^{13}_{7}N$$

$$^{13}_{7}N \longrightarrow ^{13}_{6}C + ^{0}_{+1}e$$

iii) Conversion of stable isotope of nitrogen ($^{14}_{7}N$) into radioactive isotope of oxygen ($^{17}_{8}O$).

$$^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{9}F + ^{1}_{0}n$$

$$^{17}_{9}F \longrightarrow ^{17}_{8}O + ^{0}_{+1}e$$

iv) Conversion of isotope of sodium ($^{23}_{11}Na$) into magnesium isotope ($^{24}_{12}Mg$).

$$^{23}_{11}Na + ^{2}_{1}H \longrightarrow ^{24}_{11}Na + ^{1}_{1}H$$

$$^{24}_{11}Na \longrightarrow ^{24}_{12}Mg + ^{0}_{+1}e$$

v) Conversion of isotope of aluminium ($^{27}_{13}Al$) into magnesium isotope ($^{24}_{12}Mg$).

$$^{27}_{13}Al + ^{1}_{0}n \longrightarrow ^{24}_{11}Na + ^{4}_{2}He$$

$$^{24}_{11}Na \longrightarrow ^{24}_{12}Mg + ^{0}_{+1}e$$

4.2 Nuclear reactions

Nuclear reactions are those which change the identity or characteristics of an atomic nucleus, induced by bombarding it with an energetic particle. The bombarding particle may be an alpha particle, a gamma-ray photon, a neutron, a proton, or a heavy ion. In any case, the bombarding particle must have enough energy to approach the positively charged nucleus to within range of the strong nuclear force. A typical nuclear reaction involves two reacting particles, a heavy target nucleus and a light bombarding particle and produces two new particles, a heavier product nucleus and a lighter ejected particle. Ernest Rutherford in 1919 first studied the nuclear reaction in which he bombarded nitrogen with alpha particles and identified the ejected lighter particles as hydrogen nuclei or protons and the product nuclei as a rare oxygen isotope. The first nuclear reaction produced by artificially accelerated particles (1932) was studied by English physicists J.D. Cockcroft and E.T.S. Walton. Lithium was bombarded with accelerated protons and two helium nuclei, or alpha particles were produced[1]. Nuclear fission and nuclear fusions are two important types of nuclear reactions.

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[1] Adam Augustyn, Editor Encyclopedia Britannica

4.2.1 Nuclear Fission Reactions

The splitting of a heavy nucleus into two nuclei of intermediate mass is called s Nuclear Fission reaction. These reactions are accompanied by liberation of some lighter particles such as neutron along with lot of energy. Of the natural nuclides, only Uranium-235 undergoes fission process when struck by slow moving neutron. The uranium-235 nucleus absorbs that neutron, which supplies sufficient energy to pass the activation energy barrier and thus produce the fission reaction. During the reaction, a highly activated intermediate uranium-236 nucleus is produced which can be cleaved in several ways as shown below;

$$^{235}_{92}U + {}^{1}_{0}n \longrightarrow \left[{}^{236}_{92}U\right] \longrightarrow \begin{cases} {}^{139}_{56}Ba + {}^{94}_{36}Kr + 3\,{}^{1}_{0}n \\ {}^{90}_{38}Sr + {}^{144}_{54}Xe + 2\,{}^{1}_{0}n \end{cases}$$

In nuclear reaction, the smaller nuclides are more stable than the nucleus which is undergoing fission reaction. In these reactions, the mass of the product is less than the mass of the reactants due to mass defect. A loss of mass about 0.2 amu per uranium atom occurs which corresponding to a loss of 0.2 g/mole which is released as energy. On the average, approximately 200 MeV of energy and 2.5 neutrons are released in the fission of uranium-235.

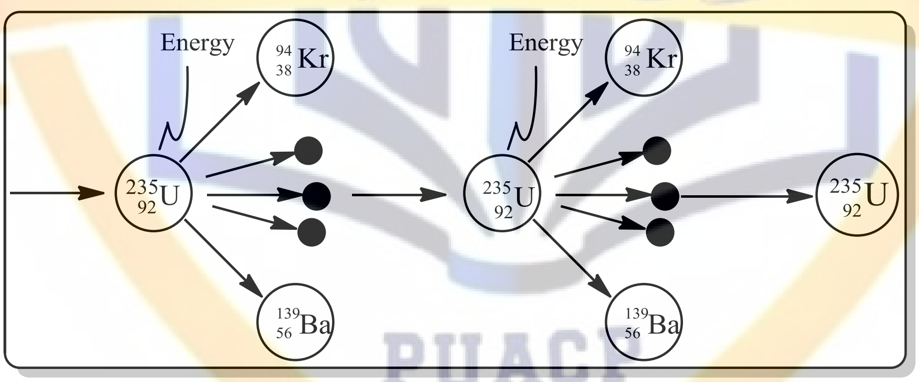

Figure 4.3: Fission Reaction of Uranium-235

Chain Reaction

Fission chain reactions happen when neutrons bombard unstable isotopes. During the bombardment, two to three neutrons are released. These neutrons are further bombarded with other three nuclei and thus the process continue and a large amount of energy is released which may or may not be controlled. Such process is called as chain nuclear reaction. If the energy is controlled then this will be used for valuable purpose such as electric power generation, and if it is uncontrolled then it will be used in atomic bombs.

Critical Mass

The minimum amount of fissionable material required to sustain the chain reaction is called as Critical Mass. Mass below the critical mass are said to be Sub Critical Mass. The mass which is greater than critical mass is said to be super critical mass.

4.2.2 Nuclear Fusion Reaction

Nuclear Fusion Reaction is the reaction in which two or more nuclei combine, forming a new element with a higher atomic number (more protons in the nucleus). Nuclear Fusion reaction is also called as **Thermonuclear Reaction**, because it occurs at ultrahigh temperature about 10^8 ºC. During reaction, there is always difference in masses between reactants and products. The difference in mass is the release of large amounts of energy. This difference in mass arises due to the difference in atomic binding energy between the atomic nuclei before and after the reaction. The energy released in fusion is related to $E = mc^2$ (Einstein's famous energy-mass equation). On earth, the most likely fusion reaction is Deuterium–Tritium reaction. Deuterium and Tritium are isotopes of hydrogen.

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + 17.6\ \mathrm{MeV} $$

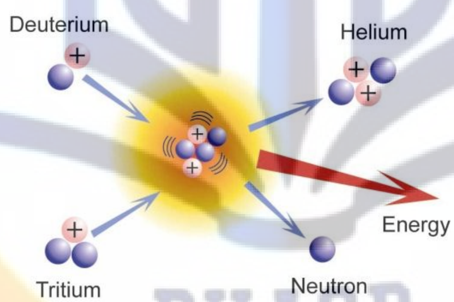

Figure 4.4: Fusion reaction of helium and deuterium

This means that the lighter elements, such as Hydrogen and Helium, are in general more fusible; while the heavier elements, such as Uranium and Plutonium are more fissionable as shown in Figure 4.4.

In thermonuclear weapons, a fission reaction is used to provide high energy, needed to initiate the Fusion reaction because it is much more difficult to bring about the nuclei closer to each other due to their positive charges. To overcome the repulsive barrier, high kinetic energy about 100 million ^{o}C temperature is required which is obtained from fission reaction. At this high temperature no atom exists, and a system contains only a mixture of nuclei and electrons which is called as plasma. An ordinary hydrogen bomb is surrounded by a shell of lithium deutride. Neutrons from fission reaction are captured by lithium nuclei;

$$^{6}_{3}Li + ^{1}_{0}n \longrightarrow ^{4}_{2}He + ^{3}_{1}H + \text{Tremendous energy}$$

The obtained high energy released during fission reaction is used for fusion reaction as tritium fused with deuterium.

$$^{2}_{1}H + ^{3}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n + \text{Tremendous energy}$$

Research into developing controlled Thermonuclear Fusion for civil purposes also started in the 1950s, and it continues to this day.

4.3 Uses of Radioactive Isotopes

Some important uses of radioactive isotopes in various fields of life are discussed in this section.

1. Uses of Radioisotopes as Radioactive Traces

*A **radioactive tracer** is a very small amount of radioactive isotope added to the chemical, biological or physical system to study the behavior of the system.*

Radioisotopes as tracers are used in many research areas such as physical, chemical and biological systems. The tracers behave just like a nonradioactive isotope. Very small quantities of radioactive material can be detected easily. This property can be used to trace the progress of some radioactive material through a complex path.

Using tracing techniques, research is also conducted with various radioisotopes which occur naturally in the environment and to examine the impact of human activities. Sewage from ocean outfalls can be traced in order to study its dispersion. Small leaks can be detected in complex systems such as power station heat exchangers. Flow rates of liquids and gasses in pipelines can be measured accurately, as can the flow rates of large rivers.

As tracers, radioactive material can be used;

(i) To diagnose the diseases

(ii) To check the function of thyroid glands: The patient is made to drink a solution of sodium iodide, doped with radioactive iodine-131, the most of it will end up in the thyroid gland. A special camera can capture the radiation emitted by the iodine-131, and an image of the gland can be constructed. An assessment can then be made about the shape, size and functioning of the gland.

(iii) Test the cancer growth
(iv) To find out the brain tumors
(v) To check the circulation of blood in veins and arteries
(vi) To check the depth of oceans
(vii) To check the small leaks in pipes in power stations
(viii) To check the flow rate of liquids and gases in pipelines
(ix) To check the flow rate of water in rivers
(x) To check the internal flow of materials in a blast furnace
(xi) Used to study soil movement and degradation[2].

2. Uses of Radioactive Traces in Chemistry[3]

In chemistry, radioactive material can be used as;

(i) **To study rate of exchange of reaction:** The rate of some exchange reactions can be studied by using tracers. For example, the electron interchange between Fe^{+3} to Fe^{+2} can be studied using radioactive $^{55}Fe^{+3}$ ion with nonradioactive Fe^{+2} ions.

$$^{55}Fe^{+3} + Fe^{+2} \longrightarrow {}^{55}Fe^{+2} + Fe^{+3}$$

(ii) **Hydrolysis of Esters:** Hydrolysis of esters has been studied by using radioactive O^{18} isotope. This technique is used to find out the mechanism of the hydrolysis reaction of alcohols.

$$R\text{-}CO\text{-}OR` + H\text{-}O^{18}\text{-}H \longrightarrow R\text{-}CO\text{-}O^{18}\text{-}R + R`OH$$

(iii) **Photosynthesis:** The mechanism of photosynthesis in plants can be studied by using CO_2 containing radioactive oxygen, O^{18} in the presence of water (H_2O) containing normal oxygen, O^{16}. It was observed that O^{18} of CO_2 goes to sugar and water while water is evolved as free oxygen (O_2). Thus it is concluded that free oxygen evolved in the process photosynthesis comes from H_2O instead from CO_2.

$$6\,CO_2^{18} + 12\,H_2O \longrightarrow C_6H_{12}O_6^{18} + 6\,H_2O^{18} + 6\,O_2$$

3. Uses of Radioactive Traces in Industry

Radioactive isotopes have many applications in industries both in the field of research as well as in process control. For example;

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[2] Kamen, M. D. (2016). *Radioactive tracers in biology: An introduction to tracer methodology* (Vol. 1). Elsevier.
[3] Anderson, I. D. K., Gonzalez, M. E., & Valenti, N. P. (1995). *U.S. Patent No. 5,474,937*. Washington, DC: U.S. Patent and Trademark Office.

(i) **Self-Diffusion of Metals**: Self diffusion phenomenon in metals (movement of metal atoms in the crystal lattice) can be studied using radioactive isotopes.

(ii) **As Catalyst**: Gamma rays obtained from Co^{60} have been used as catalyst in the preparation of ethyl bromide (C_2H_5Br) from the reaction of ethene ($CH_2=CH_2$) and HBr.

(iii) **Mechanism of Reactions:** Radioactive isotope of carbon C^{12} has been used to find out the mechanism involved in many chemical reactions in industries as well as in research work. For example, the mechanism in the preparation of polymers, alkylation etc can be found by this method.

(iv) **Uniform Mixing**: Uniformity of mixing of petrol, lubricating oil and greases etc can be achieved by labeling one of the constituent with radioactive isotope.

4. Uses of Radioactive Traces in Agriculture[4]

In agriculture, radioactive traces are used as follows.

(i) **Uptake of Phosphorus by Plants:** When a plant grows, it absorbs phosphorus both from the soil as well as from fertilizers. To find out the usefulness of fertilizers, it is important to know what proportion of phosphorus comes from each source. For this purpose, radioactive phosphorus (P^{32}) is added in the fertilizer, and then exact proportion taken up by the plant can be determined accurately.

(ii) **Transportation of Mineral in Plants**: The transportation of mineral and other essential elements from roots to leaves and then subsequent redistribution within plants can be studied by using radioactive isotopes of various elements by radio-autography. By using this technique, the distribution of sulfur (S^{35}), is supplied in the form sulfate, in beet sugar and follow the process.

5. Uses of Radioactive Traces in Analytical Techniques

Radioisotopes have many applications in chemical analysis; some are described as following;

(i) **Isotope Dilution**: *Isotope dilution is a technique to determine the quantity of a substance in a mixture of the total volume of solution by adding a known amount of an isotope to the mixture*. After removal of a portion of the mixture, the fraction by which the isotope has been diluted provides a way of determining the quantity of substance or volume of solution.

[4] L'annunziata, M. F. (1979). *Radiotracers in agricultural chemistry*. Academic Press Inc.(London) Ltd..

(ii) **Neutron Activation** Analysis: *Neutron activation analysis is an analysis of element in a sample based on the conversation of stable isotopes to radioisotope by bombarding a sample with neutrons*. Hairs of human being contains trace amount of elements. By determining the exact amount and position of the elements in the hair shaft, we can identify whom the hair comes from.

6. Uses of Radioisotopes in the Treatment of Diseases[5]

Treatment of diseases by the use of radioisotope is called as Radiotherapy. Examples of some radiotherapy are described here.

(i) Treatment of Thyroid Complaints: Thyroid gland is present in Pituitary body. (**Thyroid Gland** is a large ductless gland in the neck which secretes hormones regulating growth and development through the rate of metabolism. While the Pituitary gland or pituitary body is the major endocrine gland, a pea-sized body attached to the base of the brain that is important in controlling growth and the functioning of the other endocrine glands). Radioactive iodine (I^{131}) is used for the treatment of certain thyroid complaints. Stable and radioactive isotopes of iodine are absorbed by the thyroid gland. Radioactive iodine destroys abnormal tissues of the thyroid gland more rapidly. In this way, the abnormal behavior of the tissues can be checked.

(ii) Treatment of Cancer Growth: Radio cobalt (Co^{60}) is used in the treatment of cancer disease. Co^{60} is a beta and gamma emitter and the radiation is focused on malicious tissue to destroy it.

(iii) Blood Disorder: Radio phosphorus in the form of phosphate is widely used in the treatment of blood related diseases such as blood disorder.

(iv) Skin Diseases: Radio phosphorus (P^{30}) is used to cure the skin disease.

7. Determination of the Age of Earth by Rock Dating Method

The age of rock and other minerals give an approximate idea about the age of earth. It gives information about the age of stone or mineral?

8. Determination of Age of Various Objects by Radiocarbon Dating Method

The age of recent objects such as animals and vegetables origin like a piece of wood or animal fossils can be determined by Radio-Carbon Dating Method.

In this method, the age of sample of wood consists of determining the ratio of the amount of C^{14} to C^{12} in both pieces of wood i.e. in fresh piece of wood and in dead piece. As long as the plant is alive, the ratio of C^{14} to C^{12} atoms in the wood of plant is same as in atmosphere, but when the tree is cut, the ratio of C^{14} to C^{12} begins to decrease continuously due to decrease of C^{14} in the plant. This decrease of the amount of C^{14} is due to continuous

[5] Hoskin, P. J. (Ed.). (2007). *Radiotherapy in practice-radioisotope therapy*. Oxford University Press.

disintegration emitting beta radiations. From this technique the age of the plants can be determined.

4.4 Nuclear Hazards and Safety Measures

Risk or danger to human health or the environment exposed by the radiation emanating from the atomic nuclei is called as nuclear hazard. Nuclear hazard is an actual or potential release of radioactive material at a commercial nuclear power plant or a transportation accident. Nuclear radiations have found very important and useful applications in different domains; however, these radiations are detrimental and injurious to biological systems-animals and plants when exposure is above the permissible levels. Nuclear hazard and safety measures are discussed in this section.

4.4.1 Nuclear Hazards

The two best known examples illustrating the effect of fallout contamination are the bombing of Hiroshima and Nagasaki, Japan in 1945 and the Chernobyl Nuclear Power Station disaster in April 1986. Within five years of the American bombing of Japan, as many as 225,000 people had died as a result of long-term exposure to radiation from the bomb blast, chiefly in the form of fallout[6]. The disaster at the Chernobyl Nuclear Power Station in Ukraine on April 26, 1986 produced a staggering release of radioactivity. In ten days at least 36 million curies spewed across the world[7]. The fallout contaminated approximately 2,590 sq. km of farmland and villages in the Soviet Union. In addition to the hundreds killed at the time of the explosion, scientists predict the eventual Soviet death toll from the Chernobyl accident is around 200,000; the estimated mortality in Western Europe may be around 40,000.

Radiation and nuclear hazards, which include nuclear power plants, industrial radiation devices, and nuclear weapons, result from energy and particles released from the nuclei of the atoms. The energy released during a nuclear explosion, which comes from energy released from electron shells around the nuclei, can be more than 1 million times greater than that of a conventional explosion. Radiation includes alpha radiation (two protons and two neutrons released from the nucleus), beta radiation (small positively- or negatively-charged particles released from the nucleus), gamma and x-rays (energy and neutrons.

Types of Nuclear Hazards

[6] Selden, K. I., & Selden, M. (2015). *The Atomic Bomb: Voices from Hiroshima and Nagasaki: Voices from Hiroshima and Nagasaki*. Routledge.
[7] https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/chernobyl-accident.aspx

There are two main types of nuclear hazards:
(i) Contamination hazards due to ingestion of small quantity of radioactive material.
(ii) Radiation hazards due to exposure of human boy to external sources of radiations.

Time of exposure, distance from the source of exposure, and level of shielding are the three major variables in determining injury from radiation. Alpha radiation travels only a few inches and can be stopped by a piece of paper, but can cause lung cancer if inhaled. Beta radiation can travel up to 2 meters, is absorbed by light-weight shielding materials such as aluminum, and can burn the skin. Gamma and x-rays travel several hundred meters, can penetrate the entire body, and damage cell tissues and DNA. Acute radiation sickness can result from large doses or radiation, and cancers can result from a broad range of exposures. Hot spots for nuclear explosions include India, Pakistan, Iran, and North Korea. Nuclear power plant hazards are greatest at plants designed and built by the former Soviet Union in Eastern Europe and Central Asia.

The sources of radioactive wastes are:

1) Natural sources: Solar radiation, Radionuclides in the earth Crust, Human Internal radiation,

environmental Radiations.

2) Anthropogenic Sources: The sources of such waste include : 1) nuclear weapon testing or

detonation; 2) the nuclear fuel cycle, including the mining, separation, and production of

nuclear materials for use in nuclear power plants or nuclear bombs; (3) accidental release of

radioactive material from nuclear power plants.

PUACP

Radiation Effects

There are two main types of radiation health effects. Detrimental/injurious effects occur only if the dose or dose rate (i.e. the dose per unit time) is greater than some threshold value. The effects occur early and are more severe for higher doses and dose rates. Examples are acute radiation syndrome, skin burn and sterility. If the dose is low or delivered over a longer period of time, there is a greater opportunity for the body's damaged cells to repair themselves; however, harmful effects may still occur. Effects of this type, called stochastic, are not certain to occur, but their likelihood increases for higher doses, whereas the timing and severity of an effect do not depend on the dose. Examples are cancers of various types[8].

When radiation passes through matter it transfers some of its energy in the absorbing material by ionization or excitation of the atoms. It is ionization of atoms in tissue, accompanied by chemical changes, that causes the harmful biological effects of radiation. For example, when ionizing radiation passes through cellular tissue, it produces charged water molecules. These break up into free radicals, which are highly reactive chemically and can alter important molecules such as deoxyribonucleic acid (DNA) in cells. Radiation can also ionize DNA molecules directly. These effects of ionization can lead to biological effects, including cell death and abnormal cell development.

Basic Principles of Radiation Safety

The detrimental and injurious effects can be avoided or minimized by adopting the following precautionary measures.

1. The distance between the radiation source and personnel exposed should be increased. Usually doubling the distance from the source will reduce the radiation exposure by a factor of four.
2. Allow only the operator in the x- ray room when exposures are made. Always try to restraint the animal or subject by anesthesia. Always use a cassette holding device especially in large animal radiography. The exposure should be made behind the Shielding screen or at least 6 feet away from the source.
3. Fluoroscopy should never be used as a substitute for a non-motion radiographic procedure as amount of radiations is extremely large in fluoroscopy.
4. The lead shielding material in the gloves and aprons reduces the dose of scatter radiation well below 1/12th of the scatter radiation dose. Aprons should have a minimum of 0.25 mm lead equivalent for voltages upto 100 KV. Check the shielding material periodically for cracks etc.
5. Never fold the protective aprons. Gloves and goggles should be used during exposure. X-Ray room should be located away from the traffic and public places to prevent the inadvertent exposure of the public.
6. Make sure workers display signs warning other persons that radiation- emitting equipment is in use
7. Check the equipment periodically for possible leakage. Display warning signs near the location of X-Ray unit regarding potential hazards. The wall of the X-Ray room should be at least 22 cm thick and should be of concrete in to which iron may be introduced.

[8] https://www.who.int/ionizing_radiation/a_e/Basic%20Info%20leaflet-E%20march%202005.pdf?ua=1

8. Use of intensifying screens minimizes the factors. Provide workers with instruction and training on the health effects associated with radiation exposure and the safe use of equipment.
9. Users may receive a dosimeter badge or ring to monitor radiation exposure. Two film badges should be used one at the belt level to monitor whole body exposure and the other above the protective apparel, at the neckline, to estimate exposure to the skin of the head, neck and eyes. Film badges or thermo luminescent dosimeters can be obtained commercial sources, and at periodic intervals these monitoring devices should be sent for calibrating.
10. Regular testing for radioactive contamination must be conducted.
11. Pregnant woman and persons under 18 years of age should not be involved in radiographic work as it may adversely affect the growing fetus and the gonads of the persons exposed which may cause sterility or infertility.

4.7 Stability of Nuclei

The nuclei are made up of protons and neutrons. The protons would tend to fly apart due to repulsive forces between them. But the neutrons hold the protons together within the nucleus. A nucleus is stable if it cannot be transformed into another configuration without adding energy from the outside. Of the thousands of nuclides that exist, about 250 are stable. The stability of a nucleus largely depends on the neutron-to-proton ratio (n/p) in the nucleus. Figure 4.5 reveals the neutron-to-proton ratios for all known stable elements. Each point on the graph indicates the number of protons and neutrons in a particular stable nucleus. The straight line in Figure 4.5 represents nuclei that have a 1:1 ratio of protons to neutrons (n:p ratio). It is observed that the lighter stable nuclei, in general, have equal numbers of protons and neutrons. For example, nitrogen-14 has seven protons and seven neutrons. Heavier stable nuclei, however, have increasingly more neutrons than protons. For example: iron-56 has 30 neutrons and 26 protons, an n:p ratio of 1.15, whereas the stable nuclide lead-207 has 125 neutrons and 82 protons, an n:p ratio equal to 1.52. This is because larger nuclei have more proton-proton repulsions, and require larger numbers of neutrons to provide compensating strong forces to overcome these electrostatic repulsions and hold the nucleus together.

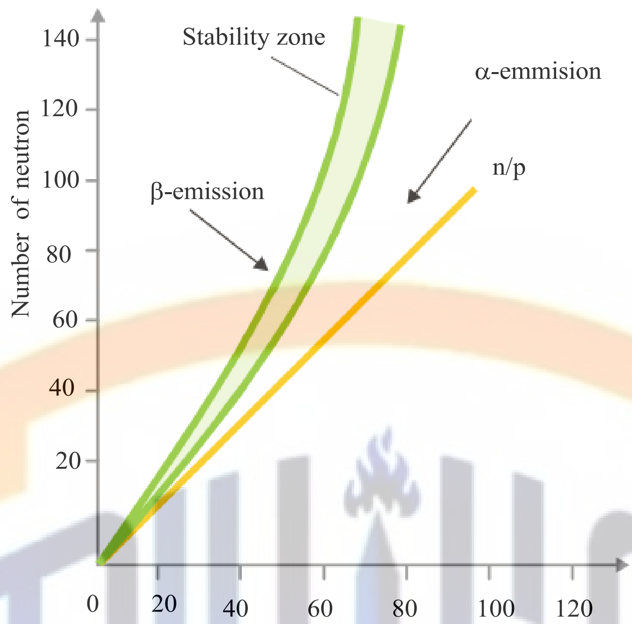


Figure 4.5 Neutron-proton ratio in the elements

The nuclei that are to the left or to the right of the band of stability are unstable and exhibit radioactivity. They spontaneously decay into other nuclei that are either in, or closer to, the band of stability due to unfavorable n/p ratio. They emits α- or β- particles so as to move into the stability range. These nuclear decay reactions convert one unstable isotope (or radioisotope) into another, more stable, isotope. A nucleus that is above the stability belt emits a β-particle whereby a neutron is converted to proton. Thus n/p decreases and the nucleus becomes more stable or enters the stability belt. For example,

$$^{14}_{6}C \longrightarrow\ ^{14}_{7}N + \ ^{0}_{-1}\beta$$

n/p 1.33 1.0

A nucleus whose n/p lies below the stability belt emits an α-particle and loses 2 protons and 2 neutrons that results in a net increase of n/p and the new nucleus may enter the stability belt. For example,

$$^{238}_{92}U \longrightarrow\ ^{234}_{90}Th + \ ^{4}_{2}\alpha$$

n/p 1.565 1.0

The radioactive nuclei continue to emit α- or β-particles, one after the other, till a stable nucleus is the formed as end product

Several observations may be made regarding the relationship between the stability of a nucleus and its structure. Nuclei with even numbers of protons, neutrons, or both are more likely to be stable. Nuclei with certain numbers of nucleons, known as magic numbers, are stable against nuclear decay. These numbers of protons or neutrons (2, 8, 20, 28, 50, 82, and 126) make complete shells in the nucleus. These are similar in concept to the stable electron shells observed for the noble gases.

The relative stability of a nucleus is correlated with its binding energy per nucleon, the total binding energy for the nucleus divided by the number or nucleons in the nucleus.

4.8 Nuclear Transformation

Nuclear transformation or transmutation is the conversion of one element or an isotope into another element. Because any element (isotope) is defined by its number of proton and neutron in its atoms and nuclear transmutation occurs in any process where this number is changed. Transmutation can be achieved either by nuclear reactions (in which an outside particle reacts with a nucleus) or by radioactive decay (where no outside particle is needed).

All types of transmutation are caused by either decay (naturally) or nuclear reaction (artificially). Natural transmutation created most of the heavier chemical elements in the universe. One type of natural transmutation observed when certain radioactive elements present in nature spontaneously decay by a process that causes transmutation, such as alpha or beta decay. For example, conversion of potassium-40 into argon-40 is a type of natural transformation of one element into other. An α-emission reduces the atomic mass by 4 and atomic number by 2. For example, Radium decays by α-emission to form a new element Radon.

$$\underset{\text{(Parent)}}{{}^{226}_{88}\mathrm{Ra}} \longrightarrow \underset{\text{(Daughter)}}{{}^{222}_{86}\mathrm{Rn}} + {}^{4}_{2}\alpha$$

A β-emission increases the atomic number by 1 with no change in atomic mass.

An example of β-decay is the conversion of lead-214 to bismuth-214,

$${}^{214}_{82}\mathrm{Pb} \longrightarrow {}^{214}_{83}\mathrm{Bi} + {}^{0}_{-1}\beta$$

Artificial transmutation may occur in equipment that has enough energy to cause changes in the nuclear structure of the elements. Such equipments include particle accelerators. Conventional fission power reactors also cause artificial transmutation, not from the power of the machine, but by exposing elements to neutrons produced by fission from an artificially produced nuclear chain reaction. For instance, when a uranium atom is bombarded with slow neutrons, fission takes place. This reaction releases, on average, 3 neutrons and a large amount of energy. The released neutrons then cause fission of other uranium atoms, until all of the available uranium is exhausted. This is called a chain reaction. Artificial nuclear transmutation has been considered as a possible mechanism for reducing the volume and hazard of radioactive waste.

In 1919, Ernest Rutherford discovered that it is possible to change the nucleus of one element into the nucleus of other element. Rutherford bombarded nitrogen-14 with alpha particles from the radioactive decay of radium and oxygen-17 and a proton.

$$^{14}_{7}N + ^{4}_{2}He \longrightarrow ^{17}_{8}O + ^{1}_{1}H$$

In this reaction the nucleus of nitrogen has changed into the nucleus of oxygen.

Similarly, bombardment of beryllium nucleus with alpha particles generates a nucleus of carbon and a particle having mass equal to the mass of neutron. This particle is named Neutron by Chadwick in 1932.

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

Irene and Joliot-Curie in 1933, treating light elements such as born or aluminium with alpha particles, detected the emission of positrons and neutrons.

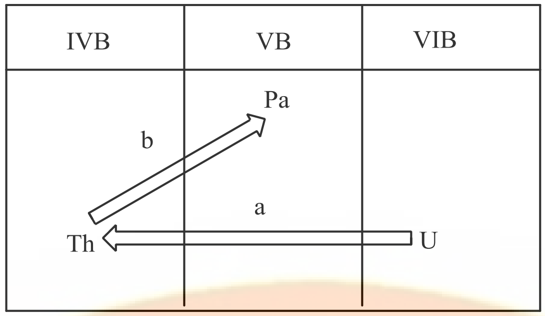
$$^{27}_{13}Al + ^{4}_{2}He \longrightarrow ^{30}_{15}P + ^{1}_{0}n$$

$$^{30}_{15}P \longrightarrow ^{30}_{14}Si + ^{0}_{1}e$$

Phosphorus-30 was the first radioactive element which was produced in laboratory. Since then thousands of radioactive isotopes have been produced.

4.8. The Group Displacement Law

The position number of an element in a group of the periodic table corresponds to its atomic number. If the atomic number of a given element is changed, its group also changes accordingly. We know that an α-emission decreases the atomic number of the parent element by 2 and a β-emission increases the atomic number by 1. Therefore, in an α-emission, the parent element will be displaced to a group two places to the left and in a β-emission, it will be displaced to a group one place to the right. This is called the Group Displacement Law. It was first purposed by Fajans and Soddy (1913) and is often named after them as 'Fajans-Soddy Group Displacement Law'. Group Displacement law is illustrated in the Figure below.



Group Displacement law

4.10 Measurement of Nuclear Radiations

Nuclear radiations can be detected and measured quantitatively by a number of methods; the important methods are discussed in this section.

4.10.1 Geiger–Muller Counter

The Geiger counter is an instrument used for measuring ionizing radiation used widely in such applications as experimental physics and the nuclear industry. It detects ionizing radiation such as alpha particles, beta particles and gamma rays using the ionization effect produced in a Geiger–Muller tube. It consists of a cylindrical metal tube (cathode) and a central wire (anode). The tube is filled with argon gas at reduced pressure (0.1 atm). A potential difference of about 1000 volts is applied across the electrodes. When an α- or β-particle enters the tube through the mica window, it ionizes the argon atoms along its path.

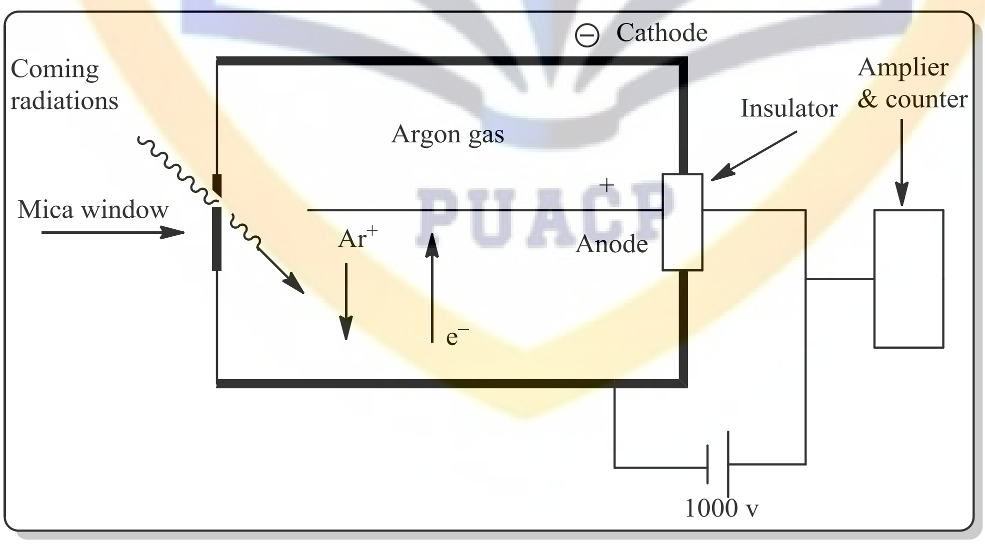


Figure 4.6: Schematic diagram of Geiger–Muller counter

The argon ions (Ar^+) are drawn to the cathode and electrons to anode. Thus for a fraction of a second, a pulse of electrical current flows between the electrodes and completes the circuit around. Each electrical pulse marks the entry of one α- or β-particle into the tube and is recorded in an automatic counter. The number of such pulses registered by a radioactive material per minute gives the intensity of its radioactivity.

4.10.2 Wilson Cloud Chamber

The cloud chamber, also known as the Wilson chamber, is a particle detector used for detecting ionization radiation. Charles Thomson Rees Wilson (1869–1959), a Scottish Physicist, invented the cloud chamber. The chamber contains air saturated with water vapors. When the piston is lowered suddenly, the gas expands and is super cooled. As an α- or β-particle passes through the gas, ions are created along its path. These ions provide nuclei upon which droplets of water condense. The trail or cloud thus produced marks the track of the particle. The track can be seen through the window above and immediately photographed. Similarly, α- or β-particles form a trail of bubbles as they pass through liquid hydrogen. The bubble chamber method gives better photographs of the particle tracks.

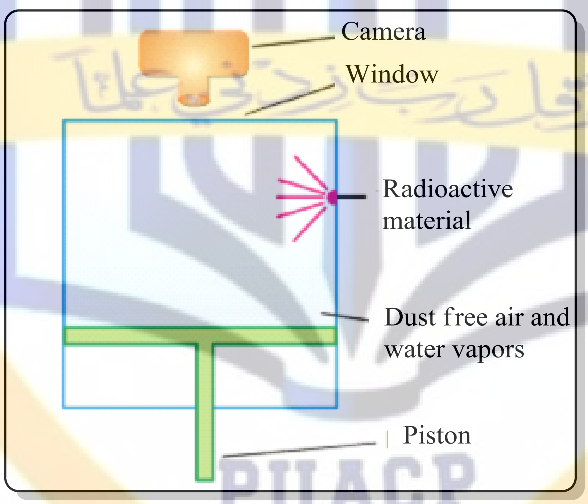


Figure 4.7: Schematic diagram of Wilson's Cloud Chamber

4.10.3 Ionization Chamber

This is the simplest instrument used to measure the strength of radiation. An ionization chamber is fitted with two metal plates which are separated by air. When radiation passes through this chamber, it knocks out electrons from gas molecules and cations are formed. The electrons migrate to the anode and cations to the cathode. Thus a small current passes between the plates. This current can be measured with an ammeter, and indicates the strength of radiation which passes through the ionization chamber. In an ionization chamber called Dosimeter, the total amount of electric charge passing between the plates in a given time is measured. This is proportional to the total amount of radiation which passes through the chamber.

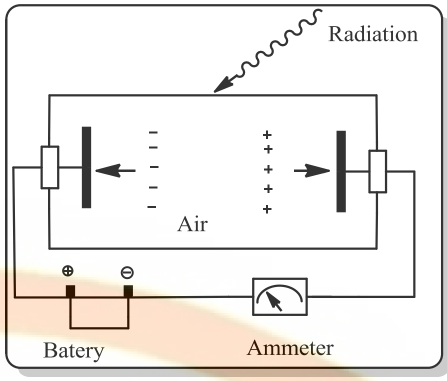


Figure 4.8: Ionization chamber

4.10.4 Film Badges

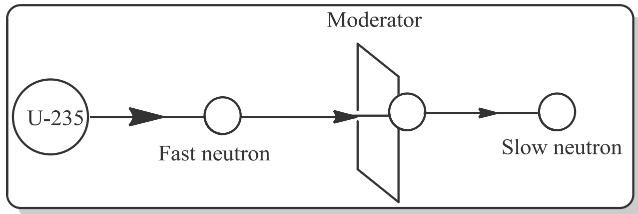
A film badge consists of a photographic film placed in a plastic holder. Radiation falls onto it and darken the grains of silver in photographic film. The film is developed and viewed under a powerful microscope. When the α- or β-particles pass through the film, they leave a track of black particles. These particles can be counted. In this way the type of radiation and its intensity can be known. However, γ-radiation darkens the photographic film uniformly. The amount of darkening is proportional to the quantity of radiation. A film badge is an important device to monitor the extent of exposure of persons working near the radiation source.

4.11 Nuclear Reactors

It has been possible to control fission of U-235 so that energy is released slowly at a usable rate. A nuclear reactor, formerly known as an atomic pile, is a device used to initiate and control a self-sustained nuclear chain reaction. Nuclear reactors are used at nuclear power plants for electricity generation and in nuclear marine propulsion.

The main components of a nuclear reactor are:

1. **Fuel in which fission occurs and heat is generated**: U-235 fuel rods which constitute the 'fuel core'. The fission of U-235 produces heat energy and neutrons that start the chain reaction.
2. **Moderator to reduce the energy of the neutrons:** The most commonly used moderator is ordinary water. Graphite rods are sometimes used. Neutrons slow down by losing energy due to collisions with atoms/molecules of the moderator.



3. **Coolant to remove the heat from the fuel elements:** Water used in the reactor serves both as moderator and coolant. Heavy water (D_2O) is even more efficient than light water.
4. **Control rods which control the rate of fission of U-235:** These are made of boron-10 or cadmium that absorbs some of the slowed neutrons.

$$^{10}_{5}B + ^{1}_{0}n \longrightarrow ^{7}_{3}Li + ^{4}_{2}He$$

Hence the chain reaction is prevented from going too fast.

5. **Concrete shield** which protects the operating personnel and environments from destruction in case of leakage of radiation.

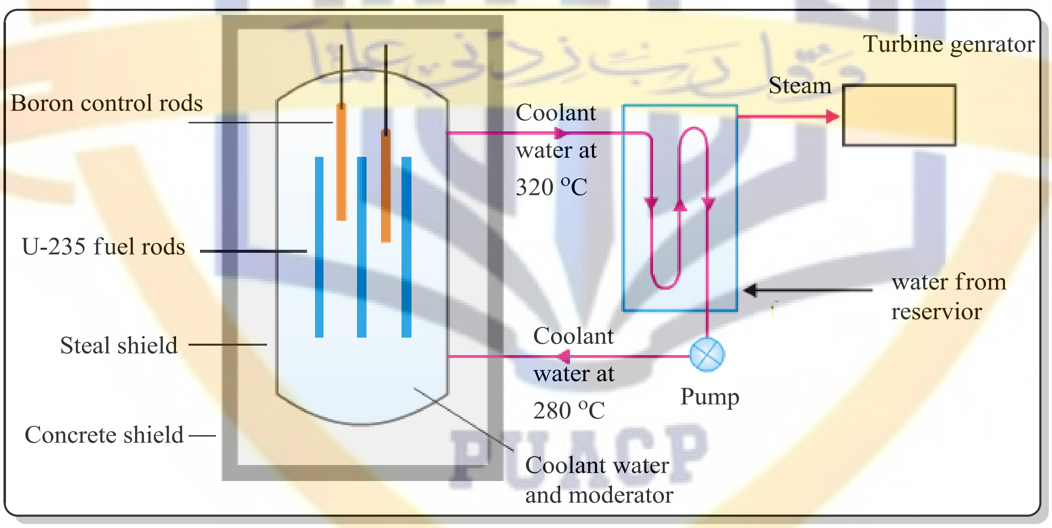


Figure 4.10: Schematic diagram of a typical nuclear reactor

Light-water nuclear power plant: 'Light-water reactors' are commercially used nuclear reactors. In this type of reactor, U-235 fuel rods are submerged in water. Water acts as coolant and moderator. The control rods of boron-10 are inserted or removed automatically from spaces in between the fuel rods. The heat emitted by fission of U-235 in the fuel core is absorbed by the coolant. The heated coolant (water at 300°C) then goes to the exchanger. Here the coolant transfers heat to sea water or river water which is converted into steam. The steam then turns the turbines, generating electricity. A reactor once started can continue to function and supply power for generations. About 15 per cent of consumable electricity in U.S.A. today is provided by light water reactors.

Nuclear Reactor Waste: Disposal of reactor waste is another safety hazard. The products of fission, e.g., Ba-139 and Kr-92, radioactive and emit dangerous radiation for several hundred years. The waste is packed in concrete barrels which are buried deep in the earth or dumped in the sea. But the fear is that any leakage and corrosion of the storage vessels may eventually contaminate the water supplies.