NATIONAL OPEN UNIVERSITY OF NIGERIA

SCHOOL OF SCIENCE AND TECHNOLOGY

COURSE CODE: CHM 406

COURSE TITLE: NUCLEAR AND RADIOCHEMISTRY

COURSE GUIDE

CHM 406
NUCLEAR AND RADIOCHEMISTRY

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Published by
National Open University of Nigeria

Printed 2013

ISBN: 978-058-004-2

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INTRODUCTION

Nuclear and Radiochemistry is a second semester course. It is a two-credit unit course to be taking by all students offering Bachelor of Science chemistry.

Nuclear and Radiochemistry is specialised branch of chemistry that helps to shape the orientation of chemist and analyst to be able to qualitatively and quantitatively analyse radiation from radioactive samples.

Its application varies extensive and covers large number of sources of radiations ranging from homes, food, water, and air. The application of this knowledge in various human endeavours such as forensic research, archaeological studies, agriculture, medicine history, and other scientific research make this course highly important.

The level of investigating analysis has also progress in terms of volume from radiation equivalent in man (rem) to milli-radiation equivalent in man (mrem).

The course will definitely instil in you, the need not ignore even the smallest thing or substance in the environment.

WHAT YOU WILL LEARN IN COURSE

The course consists of study units and course guide. The course guide tells briefly what the course is all about and how the full understanding to be acquired.

It gives you guidance in respect of your tutor-workers assignment which will be made available in the assignment file .There will be a regular session that are related to the course.

It is advisable for you to attend these tutorial sessions. Various challenges you will meet in this field of analytical chemistry are passionately reviewed during these sessions

COURSE AIMS

The course aims at providing you an in depth but introductory understanding to analytical chemistry, thereby enhancing your correct perception of analytical or environmental materials.

COURSE OBJECTIVES

To achieve these aims stated above, the course has a set of objectives. Each study unit also has specific objectives which are included at the beginning of each unit.

You may wish to refer to them during your study to check on your progress. You should always correlate what your understanding is with the study unit objectives. By doing so you would have followed the instruction in the unit. When you go over and over the course materials with the instruction therein, you would be able to achieve the aims and the sets of objectives for the course within the stipulate time. Thus after going through this book you should be able to

- Understand the general concept of radioactivity
- Know types of radioactivity
- Know various form of electromagnetic radiations that are emitted
- Differentiate between ordinary chemical reactions and nuclear reactions
- describe what decay mode and energy are
- tell what is meant by fission and fusion
- calculate the half-life of any disintegration
- Understand general concept nuclear model
- Describe the principle upon which the models are built
- Explain collective nuclei model
- Describe the unified model for defining model
- Describe the mass-energy relationship when particles and nucleus interact
- Understand various conservation laws as they affect the nuclear reactions.
- Describe the forms of energy in the three main stages of nuclear reaction
- explain the principle underlying the measurement of radiation
- know various methods and instrument used in measuring radioactivity
- know limitation of those methods used in measuring radioactivity
- Know the applications of radioactivity in various human endeavour
- Describe about various sources of radiation exposure
- Know about the relationship before radiation and health condition
- Know about management of hazardous nuclear waste
- Understand the ways of protection from radiation exposure.

WORKING THROUGH THE COURSE

To benefit maximally from this course, you are required to read each unit very well, read the text books and other materials, as recommended at end of each unit and any other materials that may be provided by the National Open University of Nigeria.

Each unit contains self-assessment exercises and at certain points in the course you would be required to submit assignments for assessment purposes. At the end of the course, there is final examination. The course should take you a total of 17 weeks to complete. Below you will find listed all the components of the course, what you have to do and how you should allocate your time to each unit in order to complete the course on time and successfully.

This course entails that you spend a lot of time to read. I would advise that you avail yourself the opportunity of attending the tutorial sessions where you have the opportunity of comparing your knowledge with that of other learners.

THE COURSE MATERIALS

The main components of the course materials are:

1. The Course Guide
2. Study Unit
3. References/Further Reading
4. Assignments
5. Presentation Schedule.

STUDY UNITS

The study units in this course are as follow:

Module 1

Unit 1 Natural Radioactivity
Unit 2 Radioactive Decay Processes and Nature of Radioactivity

Module 2

Unit 1 Nuclear Models
Unit 2 Energetic of Nuclear Radiation

Module 3

Unit 1 Principle and Measurement of Radioactivity
Unit 2 Application of Radioactivity
Unit 3 Radiation Hazards

PRESENTATION SCHEDULE

Your course materials have important dates for the completion and submission of your TMAs and attending tutorials. You should remember that you are required to submit all your assignments by the stipulated time and date. You should guard against falling behind in your work.

ASSESSMENT

There are three aspects to the assessment of the course. First is made up of self-assessment exercises, second consists of the tutor-marked assignments and third is the written examination/end of course examination.

You are advised to do the exercises. In tackling the assignments, you are expected to apply information, knowledge and techniques you gathered during the course. The assignments must be submitted to your facilitator for formal assessment in accordance with the deadlines stated in the presentation schedule and the assignment file. The work you submit to your tutor for assessment will count for 30% of your total course work. At the end of the course you will need to sit for a final or end of course examination of about three hour duration. This examination will count for 70% of your total course mark.

TUTOR-MARKED ASSIGNMENT

The TMA is a continuous assessment component of your course. It accounts for 30% of the total score. You will be given four (4) TMAs to answer. Three of these must be answered before you are allowed to sit for the end of course examination. The TMAs would be given to you by your facilitator and returned after you have done the assignment. Assignment questions for the units in this course are contained in the assignment file. You will be able to complete your reading, references and study units. However, it is desirable in all degree level of education to demonstrate that you have read and researched more into your references, which will give you a wider view point and may provide you with a deeper understanding of the subject.

Make sure that each assignment reaches your facilitator on or before the deadline given in the presentation schedule and assignment file. If for any reason you cannot complete your work on time, contact your facilitator before the assignment is due to discuss the possibility of an extension. Extension will not be granted after the due date unless there are exceptional circumstances.

FINAL EXAMINATION AND GRADING

The end of course examination for Analytical chemistry 1 will be for about 3 hours and it has a value of 70% of the total course work. The examination will consist of questions, which will reflect the type of self-testing, practice exercise and tutor-marked assignment problems you have previously encountered. All areas of the course will be assessed.

Use the time you have between finishing the last unit and sitting for the examination to revise the whole course. You might find it useful to review your self-test, TMAs and comments on them before the examination. The end of course examination covers information from all parts of the course.

COURSE MARKING SCHEME

Assignment	**Marks**
Assignment 1 – 4	Four assignments, best three marks of the four count at 10% each – 30% of course marks.
End of course examination	70% of overall course marks.
Total	**100% of course materials.**

FACILITATORS/TUTORS AND TUTORIALS

There are 16 hours of tutorials provided in support of this course. You will be notified of the dates, times and location of these tutorials as well as the name and phone number of your facilitator, as soon as you are allocated a tutorial group.

Your facilitator will mark and comment on your assignments, keep a close watch on your progress and any difficulties you might face and provide assistance to you during the course. You are expected to mail your Tutor Marked Assignment to your facilitator before the schedule date (at least two working days are required). They will be marked by your tutor and returned to you as soon as possible.

Do not delay to contact your facilitator by telephone or e-mail if you need assistance.

The following might be circumstances in which you would find assistance necessary, hence, you would have to contact your facilitator if:

- You do not understand any part of the study or the assigned readings.
- You have difficulty with the Self-Assessment Exercise.
- You have a question or problem with an assignment or with the grading of an assignment.

You should endeavour to attend the tutorials. This is the only chance to have face to face contact with your course facilitator and to ask questions which are answered instantly. You can raise any problem encountered in the course of your study.

To gain much benefit from course tutorials prepare a question list before attending them. You will learn a lot from participating actively in discussions.

SUMMARY

Nuclear and Radiochemistry is a course that intends to provide concise introduction to a specialised area of chemistry (Nuclear and Radiochemistry). The course study units are well structured and supported by eyes opening questions. No doubt, this is a best beginning into the world of analytical chemistry.

Upon completing this course, you will be equipped with the needed basic concept and principle to give you good foundation to this investigating chemistry.

You should endeavour to read very well, ruminate over what you’ve read, go through the self-assessment question and TMA provided in each study unit. You will definitely appreciate this course.

Wish you success in your studies.

MAIN COURSE

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MODULE 1 FUNDAMENTAL CONCEPT OF RADIO ACTIVITY

UNIT 1 NATURAL RADIOACTIVITY

CONTENTS

1.0 INTRODUCTION

Radioactivity is a phenomenon in which some elements emit small particles called radiation, to form another element. This is in contrast to the accepted Dalton postulate of indestructibility of an atom. However, only elements with unstable nuclei known as radioactive are capable of undergoing natural radioactivity while stable nuclei do not. All elements having atomic number greater than 83 are radioactive and they undergo nuclear transmutation (nuclear reaction) which differ significantly from ordinary chemical reactions.

The knowledge of radioactivity has contributed immensely to medicine, archeology, scientific research, industry, engineering and agriculture.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- define radioactivity and terms used in radioactivity
- state the types of radioactive reactions

- discuss the types of electromagnetic radiations that are emitted
- differentiate between ordinary chemical reactions and nuclear reactions.

3.0 MAIN CONTENT

3.1 Radioactivity: Natural and Artificial

With exception of hydrogen ($^{1}_{1}H$), every atom of an element has a nucleus which consists of neutrons and protons, with electrons occupying important empty space around the nucleus. The nucleus is a minute fraction of total volume of atom, yet nearly all the mass of an atom resides in the nucleus. Thus, nuclei are extremely dense. It has been shown experimentally that nucleus of all elements has approximately the same density of 2.4 x 10^{14} g/cm^3. Table 1.0 shows the general properties of basic components of an element.

Table 1.0: Basic Constituents of an Atomic Element

Particle	Mass	Charge
Electron (e^-)	0.00054858 amu	-1
Proton (P)	1.0073 amu	+1
Neutron (n)	1.0087 amu	None

The ratio of number of neutron to proton in any nucleus confirms the stability of the nucleus and also influence nuclear reaction is called neutron – proton ratio.

The neutron – proton ratio of an element dictates which if element will naturally undergoes radioactivity or not.

3.2 Neutron - Proton Ratio and Nuclear Stability

The principal factor that determines stability of nucleus is the neutron – proton ratio (n/p). A nucleus is said to be stable if it does not undergo radioactivity. About 275 different nuclei have no evidence of radioactive decay, hence they are very stable. 157 nuclides out of it have even number of proton and even number of neutron (even – even nuclei), 52 nuclides have even number of proton and odd number neutron. 50 nuclides have odd number of protons and even number of neutron while only four nuclides have odd number of both proton and neutrons. These are presented in Table 2.0

Table 2.0: Abundance of naturally occurring Nuclides

Number of particles	Even/ Odd	Even/ Odd	Even/ Odd	Even/ Odd
Number of protons	Even	Even	Odd	Odd
Number of neutrons	Even	Odd	Even	Odd
Number of such nuclides		157	50	52 4

The following are rules that guide the prediction of nuclear stability:

(i) Nuclides with "Magic number" (2, 8, 20, 28, 50, 126) of protons or a number of neutrons or a sum of the two have unusual stability.
(ii) Nuclei with even number of both protons and neutrons are generally more stable than those with odd numbers of these particles (Table 2.0).
(iii) All isotopes of the elements with atomic numbers higher than 83 are radioactive.

Figure 1.1 is a plot of the number of neutrons (*N*) versus number of protons (*Z*) for the stable nuclides (**the band of stability**). For low atomic numbers, the most stable nuclides have equal numbers of protons and neutrons (*N* _ *Z*). Above atomic number 20, the most stable nuclides have more neutrons than protons. Careful examination reveals an approximately stepwise shape to the plot due to the stability of nuclides with even numbers of nucleons.

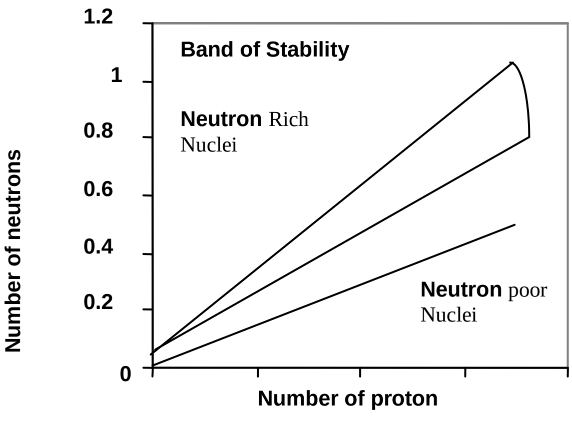

Fig. 1.1: A Plot of the Number of Neutrons (*N*) versus Number of Protons (*Z*) for the Stable Nuclides (the Band of Stability)

Nuclei whose neutron – to - proton (n/p) ratios lies outside the stable region undergoes spontaneous radioactive decay by emitting one or more particles and /or electromagnetic rays. Depending on whether the nucleus is above, below or to the right of the band of stability (Figure 1.1), it emits various types of particles discussed in 3.2 in a nuclear reaction. Note that in a nuclear reaction, changes of one particle to another occur in a pattern that shows that nuclear reaction differs from ordinary chemical reaction as summarised in Table 3.0.

Table 3.0: Comparison of Chemical Reactions and Nuclear Reactions

	Chemical Reactions	**Nuclear Reactions**
1	Atoms are rearranged by the breaking and forming of chemical bonds.	Elements (or isotopes of the same elements) are converted from one to another.
2	Only electrons in atomic or molecular orbital are involved in the breaking and forming of bonds.	Protons, neutrons, electrons, and other elementary particles may be involved.
3	Reactions are accompanied by Absorption or release of relatively small amounts of energy.	Reactions are accompanied by absorption or release of tremendous amounts of energy.
4	Rates of reaction are influenced by temperature, pressure, concentration, and catalysts.	Rates of reaction normally are not affected by temperature, pressure, and catalysts.

Both chemical and nuclear reactions are depicted by a complete chemical equation. However, two major rules guide writing the chemical equation of nuclear reaction:

(i) The sum of the mass numbers of the reactants must be equal the sum of mass number of the products
(ii) The sum of atomic number of the reactions must be equal to the atomic number of the products, this maintain charge balance.

3.3 Types of Radioactivity

Some nuclei are unstable; hence they emit sub-atomic particles or electromagnetic radiation in a phenomenon known as radioactivity. Radioactivity can be of two types namely, natural and artificial radioactivity.

Natural Radioactivity: This is a type of radioactivity that occurs spontaneously, emitting electromagnetic radiation and particles which include beta, positron and alpha particles. The occurrence of this type of decay or emission occurs, depends on the position of nuclei whether above, below or sides of the **stability/belt region**. Most naturally radioactive nuclei lie outside this belt.

Artificial radioactivity: It is a non-spontaneous form of radioactivity which requires effect of bombardment of the nuclei with sub-atomic particles. It is otherwise known as anthropogenic or induced radioactivity.

Juliot and his wife, Irene Curie discovered artificial radioactivity in 1934 in which aluminum nuclei is bombarded with He nuclei to form new element with emission of electromagnetic ray or particles:

$$ {}_{2}^{4}He \quad + \quad {}_{13}^{27}Al \quad \rightarrow \quad {}_{14}^{30}P \; + {}_{1}^{1}n $$

3.3 Particles Emission and Position of Stable Region

3.3.1 Above the Band of Stability: Neutron–Rich Region

The nuclei in this region have a very high ratio of neutron to protons than those within the belt. To reduce this ratio and move down toward the belt of stability, they undergo a nuclear reaction called Beta particle emission. A beta particle is an electron ejected from the nucleus when a neutron is converted into a proton

$$ {}_{o}^{1}n \;\rightarrow\; {}_{1}^{1}p \;+\; {}_{-1}^{0}\beta $$

Beta particle emission leads to an increase in the number of proton in the nucleus and a simultaneous decrease in the number of neutrons.

Classical examples:

i $\quad {}_{88}^{228}Ra \quad \rightarrow \quad {}_{89}^{228}Ac \quad + \quad {}_{-1}^{0}\beta$

ii $\quad {}_{40}^{97}Zr \quad \rightarrow \quad {}_{41}^{97}Nb \quad + \quad {}_{-1}^{0}\beta$

iii $\quad {}_{19}^{40}K \quad \rightarrow \quad {}_{20}^{40}Ca \quad + \quad {}_{-1}^{0}\beta$

3.3.2 Below the Band of Stability: Neutron–Poor Region

The nuclei here have lower neutron – to – proton ratios than those within the band therefore they need to increase this ratio and thereafter move up toward the belt of stability. The nuclei undergo two possible types of nuclear reaction; positron emission or electron capture (K capture).

(a) **Position emission**: It is most commonly encountered with artificially radioactive nuclei of the higher element.
Classical examples are:

i $\,^{i}_{i}P \rightarrow \,^{1}_{0}n + \,^{0}_{+1}\beta$

ii $\,^{38}_{19}K \rightarrow \,^{38}_{18}Ar + \,^{0}_{+1}\beta$

(b) **Electron captures (K capture):** Is a capture of an electron usually a 1s electron by the nucleus. The captured electron combines with a proton to form a neutron so that the atomic number decreases by one while the mass number remain the same; hence it has the same net effect as positron emission.

Classical examples:

$$^{37}_{18}Ar + \,^{0}_{-1}e \rightarrow \,^{37}_{17}Cl$$

$$^{106}_{47}Ar + \,^{0}_{-1}e \rightarrow \,^{106}_{46}Pd$$

It is important to note that some of the neutrons – poor nuclei, particularly the heavier ones, increase their neutron-to-proton ratios by undergoing alpha emission. An alpha particle is emitted from nucleus thereby reducing the mass number by 4 and atomic nunmber by 2.

Examples

$$^{238}_{92}U \rightarrow \,^{34}_{90}Th_{i} + \,^{4}_{2}He$$

3.3.3 Nuclei with Atomic Number Greater than 83

All elements with atomic numbers higher than 83, are radioactive in nature. They undergo a nuclear reaction by emitting alpha particles ($\propto$)
Classical examples are:

$$^{226}_{88}Ra \rightarrow \,^{222}_{84}e + \,^{4}_{2}\propto$$

$$^{210}_{84}Po \rightarrow \,^{201}_{84}Pb + \,^{4}_{2}\propto$$

3.3.4 Gamma Ray Emission

Gamma rays are high energy radiation, emitted when an unstable nucleus undergoes a rearrangement of its constituent particle to give more stable, lower energy nucleus. Gamma rays are often emitted along with other type of subatomic particles.

$$^{99}_{43}Tc \rightarrow {}^{99}_{43}Tc + {}^{0}_{0}\gamma$$

Note that pure gamma emitters are rare, but rather, the radiation gamma accompany either alpha or beta radiation.

SELF-ASSESSMENT EXERCISE

(i) What do you understand by the term radioactivity?
(ii) Explain the concept of neutron –to-proton ratio.
(iii) What are subatomic particles that are emitted in nuclear reaction?
(iv) Differentiate between natural and induced radioactivity.

4.0 CONCLUSION

Radioactivity is indeed a phenomenon in which electromagnetic radiation or sub-atomic particles are emitted by a nuclear reaction so as to achieve or enter stability belt. Radioactivity is of importance in medicine, agriculture and industries.

5.0 SUMMARY

In this unit, you have learnt about:

(i) the meaning of radioactivity
(ii) the differences between nuclear and ordinary chemical reaction
(iii) how to balance a chemical nuclear reaction
(iv) the rules that guide in predicting stability of a nucleus
(v) various forms of emission nuclei can undergo during nuclear reaction
(vi) differences between natural and artificial radioactivity.

6.0 TUTOR-MARKED ASSIGNMENT

i. Differentiate between nuclear and ordinary chemical reactions.
ii. Naturally occurring iodine is iodine – 127. In medicine, radioactive isotopes of iodine used are I - 125 and I- 130. Write atomic symbol for each isotope.

iii. Identify the symbol X in each of the following:

(a) ${}^{0}_{-1}X$ (b) ${}^{4}_{2}X$ (c) ${}^{1}_{0}X$ [d] ${}^{1}_{1}X$ (e) ${}^{0}_{+1}X$

iv Write short notes on various sub-atomic particles that can be emitted by nuclei in the following condition so as to enter stability belt

(a) Above the stability region

(b) Below the stability region.

7.0 REFERENCES/FURTHER READING

Timberlake, K. & Timberlaka, W. (2008). *Basic Chemistry.* Boston: Pearson Educational Inc. Pp. 524 – 538.

Choppin, G. R, Liljenzen, J. & Rydbers, J. (2002). *Radiochemistry and Nuclear Chemistry*. Woburn: Butterworth- Heinemann. Pp. 1 – 10.

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UNIT 2 RADIOACTIVE DECAY PROCESSES AND NATURE OF RADIOACTIVITY

CONTENTS

1.0 INTRODUCTION

Radioactive decay is the process by which the atomic nucleus of an unstable atom loses energy by emitting ionising particles or electromagnetic radiation. The emission is spontaneous, in that the atom decays without any physical interaction with another particle from outside the atom. Usually, radioactive decay happens due to a process confined to the nucleus of the unstable atom. Many nuclei are radioactive. This means they are unstable, and will eventually decay by emitting a particle, transforming the nucleus into another nucleus, or into a lower energy state. A chain of decays takes place until a stable nucleus is reached.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- explain the meaning of radioactive decay
- describe decay mode and decay energy
- explain the meaning of fission and fusion
- calculate the half life of any radioactive disintegration.

3.0 MAIN CONTENT

3.1 Radioactive Decay

Radioactive decay can simply be defined as a spontaneous nuclear transmutation or transformation of unstable nuclei that exist outside in the formation of stable isotope. The decay process is unaffected by pressure, temperature, chemical forms of the elements. The decay, or loss of energy, results when an atom with one type of nucleus, called the *parent radionuclide*, transforms to an atom with a nucleus in a different state, or an entirely different nucleus, either of which is named the *daughter nuclide*. Often the parent and daughter are of different chemical elements. An example of this, a carbon-14 atom (the "parent") emits radiation (a beta particle and a gamma ray) and transforms to a nitrogen-14 atom (the "daughter").The daughter nuclide of a decay event may also be unstable (radioactive). In this case, it will also decay, producing radiation. The resulting second daughter nuclide may also be radioactive. This can lead to a sequence of several decay events, phenomenon known as *decay chain* . During radioactive decay, principles of conservation apply. Some of these laws are as follows:

- conservation of energy
- conservation of momentum (linear and angular)
- conservation of charge
- conservation of nucleon number.

The type of decay that occurs depends on the position of the nuclei undergoing the decay and consequently the type of radiation that accompanies the process. Hence, the decay process is characterised by the decay period, mode and the energy without regards to either physical or chemical conditions.

3.2 Kinetics of Radioactive Decay

The particles emitted are of different kinetics or kinetic energies. All radioactive decays obey first – order kinetics therefore rate of decay at time (t) = λN

Where λ is the first order rate constant
N is the number of nuclei

Note: N at time zero is (No) and at time t is Nt

Rate of decay = K (N) as

$$(\mathrm{Ln} \left(\frac{No}{N}\right) = a\ \lambda\ t$$

Also note that: Each atom decay independently of the other, therefore stochiometrically a = 1

Therefore, $\text{Ln}\left(\frac{No}{N}\right) = \lambda t$

In nuclear chemistry, decay rate is usually expressed in terms of half life of the process. That is, the amount of time required for half of the original sample to react.

For first order process:

$t_{1/2}\ k = \frac{In^2}{k} = \frac{0.693}{k}$

Classical Example

A cobalt-60 nucleus decays with the emission of beta particle-gamma rays with half life of 5.27 years:

$${}^{60}_{27}Co \rightarrow {}^{60}_{28}N_i + {}^{0}_{-1}\beta + {}^{0}_{0}\propto$$

How much of a 3.42 mg sample remain 30.0 years

Solution

$t_{1/2} = \frac{0.693}{K}$, $K = \frac{0.693}{t_1 l_2} = \frac{0.693}{5.27} = 0.131$ yr

$\text{Ln}\ \frac{A_o}{A_1} = K_t = 0.131\ (30.0) = 3.93$

Consider the inverse of two sides

$$\frac{A_o}{A} = e3.93$$

$= 51$

$A = \frac{A_o}{51} = \frac{3.42}{51} = 0.067$ of Co – 60 = 0.067 mg.

3.3 Decay Mode and Energy

Radioactive decay involves a transition from a definite quantum state of original nuclide to a definite quantum state of product nuclide. The energy difference between the two quanta levels involved in the transition correspond to what is known as decay energy. As for types of radioactive radiation emitted, it is found that an electric or magnetic field can split such emissions into three types of beams or sub-atomic particles. They are alpha, beta, and gamma. While alpha decay is seen only in heavier elements (atomic number 52, tellurium, and above), the other two types of decay are seen in all of the elements. In analysing the nature of the decay products, it is obvious from the direction of electromagnetic forces produced upon the radiations by external magnetic and electric fields that alpha rays carried a positive charge, beta rays carried a negative charge, while gamma rays were neutral. From the magnitude of deflection, it is shown that alpha particles are much more massive than beta particles. Passing alpha particles through a very thin glass window and trapping them in a discharge tube allowed researchers to study the emission spectrum of the resulting gas, and ultimately prove that alpha particles are helium nuclei. Other experiments showed the similarity between classical beta radiation and cathode rays: They are both streams of electrons. Likewise, gamma radiation and X-rays are found to be similar high-energy electromagnetic radiation. Although alpha, beta, and gamma were found most commonly, there are other types of decay that are eventually discovered. Shortly after the discovery of the positron in cosmic ray products, it was realised that the same process that operates in classical beta decay can also produce positrons (positron emission). In an analogous process, instead of emitting positrons and neutrino, some proton-rich nuclides were found to capture their own atomic electrons (electron capture), and emit only a neutrino (and usually also a gamma ray). Each of these types of decay involves the capture or emission of nuclear electrons or positrons, and acts to move a nucleus toward the ratio of neutrons to protons that have the least energy for a given total number of nucleons (neutrons plus protons).

The mode of decay is dependent upon the particular type of nuclear involved in the reaction (position of unstable nuclei). It is important to remember that in radioactive decay, there are numbers of conservation laws as mentioned in section 3.1 that must be valid for a true decay to occur.

Consider the reaction

$X_1 + X_2 \quad X_3 + X_4$ ---------- y

Where X represents nucleus or elementary particles. X_1 and X_2 may be unstable nucleus and bombarding particles while X_3 and X_4 are products formed. So for this general reaction (y) the following number of conservation law holds.

a) The total energy of the system must be constant

$$E_1 + E_2 = E_3 + E_4$$

Where E include all forms of energy (kinetic and electrostatic energy)

b) The linear momentum must be constant

$P = MV$
$P_1 + P_2 = P_3 + P_4$

Note that $E_{kin} = P^2 /z\ m$

Where E_{kin} is kinetic energy

c) **The total charge** (proton + electron) of the system must be constant

$$Z_1 + Z_2 = Z_3 + Z_4$$

d) The mass number of the system must be constant

$$A_1 + A_2 = A_3 + A_4$$

$$M_A = z\ m\ M_H + NMn = 2.016\ u$$

e) **The angular momentum** P_I of the system must be conserved

$$(PI)_1 + (PI)_2 = (PI)_3 + (PI)_4$$

3.3.1 Alpha Decay (α)

An unstable nucleus undergoes alpha decay by emitting alpha particles.

Example:

$$^{238}_{92}U \rightarrow \ ^{34}_{90}Th_i + \ ^{4}_{2}He$$

Alpha particle cause extensive ionisation of matter. Alpha particles interact with matter which may also cause molecular excitation thereby resulting in fluorescence.

Alpha decay is observed for elements heavier than lead (Pb) and for a few nuclear that are as light as Lanthanide (Ln). The decay energy can be calculated from known atomic mass since binding energy corresponds to a:

$$E = 931.5\ \Delta M$$

ΔM = mass defect
Where $\Delta M = (M_{z-2} + M_{He} - M_z)$ i.e.
Change in mass = mass reactant – mass product

3.3.2 Beta Decay β

β decay is a spontaneous disintegration during which beta particles are emitted or electrons captured. Radioactive beta decay is depicted as β decay, it could be in any of the three forms; as electron emission β^- or $^{0}_{-1}e$, as position β^+ or $^{0}_{+1}e$ or and as election capture (EC).

(a) Electron emission β^- or $^{0}_{-1}e$:

Example:

$$^{14}_{6}Co \rightarrow ^{14}_{7}N + ^{0}_{-1}e$$

Energetic electrons cause ionisation and molecular excitation in matter, although the effect is weaker and more difficult to detect than alpha particle. Hence, there is need to amplify the effect for counting of individual beta particles.

Example:

$$^{137}Cs \longrightarrow ^{137}Ba + \beta^-$$

(b) Electron capture (EC):

The EC decay process is written as $^{A}_{Z}X \xrightarrow{EC} ^{A}_{Z+}X + v.$

The captured electron comes from one of the inner orbital of the atom. Depending on the electron shell from which the electron originates, the process is sometimes referred to as K-capture or L-capture electron. The probability of capture of electron in higher shell decreases with quantum number of shell. Therefore, the probable capture of e-from K-shell is far greater than capture of e- from L shell

The calculation of decay energy in electron capture is given as:

$$Q_{EC} = - 931.5 (M_{Z-1} - M_{Z})$$

(c) Positron decay β^+ or $^{0}_{+1}e$: In positron emission, a proton in an unstable nucleus is converted to a neutron and a positron. The neutron remain in the nucleus has positron is emitted.

Example:

$$^{24}_{13}Al \rightarrow ^{24}_{12}Mg + ^{0}_{+1}e$$

3.3.4 Gamma Ray Emission ($^{0}_{0}\gamma$)

The emission of gamma rays is always in company of emission of other particles. It is the emission which occur where transition between energy levels of same nucleus take place. Gamma rays are high energy radiation, emitted when an unstable nucleus undergoes a rearrangement of as constituent particles is give more stable, lower energy nucleus gamma rays are often emitted along with other type of particles

Examples: i. $^{99m}_{43}Tc \rightarrow ^{99}_{43}Tc + ^{0}_{0}\gamma$

ii. $^{99m}_{43}Tc + ^{99}_{43}Tc \rightarrow ^{99}_{43}Tc + ^{0}_{0}\gamma$

Note that, because Tc is in unstable form; it quickly decays to emits γ ray and becomes stable. "^{m}Tc is metastable form of Tc. Note also that pure gamma emitters are rare, but rather, the radiation accompanies either on alpha or beta radiation.

3.4 Chain Reaction

A chemical reaction in which many molecules undergo chemical reaction after one molecule becomes activated. It is a continuous process in which either splitting of bigger molecules occur to generate daughter nuclei and neutron or joining of smaller molecules occur to form big or a new parent molecule, the chemical processes known as fission and fusion respectively.

3.4.1 Nuclear Fission

Isotopes of unstable nuclei with atomic number greater than 80 are capable of undergoing a nuclear reaction called nuclear fission, in which they split into nuclei of intermediate masses and emit one or more neutrons. The energy generated is called atomic energy. Some fission reactions are spontaneous while some are not spontaneous; hence, the non-spontaneous require activation energy from bombardment. A given nucleus is split in many ways liberating enormous energy a typical example is shown below.

$$^{160}_{62}Sm \quad + \quad ^{72}_{30}Zn \quad + \quad 4^{1}_{0}n \; + \; energy$$

$$^{146}_{57}La \quad + \quad ^{37}_{50}Gr \quad + \quad 3^{1}_{0}n \; + \; energy$$

$$^{235}_{92}U + \; ^{1}_{0}n \rightarrow ^{236}_{92}U$$

$$^{144}_{55}Ba \quad + \quad ^{92}_{36}Kr \quad + \quad 3^{1}_{0}n \; + \; energy$$

$$^{144}_{55}Cs \quad + \quad ^{90}_{37}Rb \quad + \quad 2\; ^{1}_{0}n \; + \; energy$$

$$^{144}_{54}Xe \quad + \quad ^{90}_{38}Cr \quad + \quad 2\, ^{1}_{0}n \; + \; energy$$

The ^{236}U is an intermediate nucleon and is short lived producing fragment as shown above. Particles that can supply the required activation energy include neutrons, protons, alpha particles and fast electrons.

Experiment shows that when comparing the mass of original or starting materials with that of product, there is a little reduction. This missing mass has been converted into energy and is derived through Einstein equation:

E = mc2.

Where E is the energy released, m is the loss mass and c is the speed of light.

3.4.2 Nuclear Fusion

This is coming together of small nuclei to form heavy nucleus. However, the fusion reaction require a temperature of about 1, 000,000,000^{o}C to overcome the repulsion of Hydrogen nucleus, after which they are forced to undergo fusion. Spectroscopic evidence shows that sun is a tremendous fusing reactor consisting of 73% H, 26% He and 1% other element. It is a major reactor that involves fusing of deuterium, $^{2}_{1}H$ and tritium $^{3}_{1}$H at high temperature.

$$^{2}_{1}H \quad ^{3}_{1}H \quad \rightarrow \quad ^{4}_{2}He \quad + \quad ^{1}_{0}n \; + \; energy$$

3.5 Nuclear Fusion Reactor

In a fusion reactor, fusion reaction is controlled by injecting materials that absorb some neutrons so as to prevent explosion. Hence, the energy produced can be productively converted into heat source in a power plant.

There are various type of nuclear reactors, these include:

i. Light water reactor
ii. Breeder reactor.

3.6 Nature of Radiation

Although various electromagnetic rays and sub-atomic particles involved in radioactivity have been mentioned in earlier in this course, it is still necessary to reveal more about the nature of these radiations and their properties. These radiations include; alpha particles, beta particles, proton, neutron, gamma rays and positrons. Table 4.0 summarises properties of some of the common radiations.

The penetrating capacities of particles and rays are proportional to their energies. Particles such as positions are about 100 times more penetrating than the heavier ones, like alpha particles. Beta particles can be stopped by a $\frac{1}{3}$ inch trek (0.3cm) aluminum sheet. Beta particles can pierce a skin but cannot touch internal organ.

Alpha particles have low penetrating ability, hence, cannot damage or penetrate skin. However they can damage internal tissue if inhaled. The high energy gamine rays have great penetrating power as severely damage both skin as internal organ. They travel at a tie speed of high and can only be stopped by timer layers of concrete or lead.

Table 4.0: Radioactive Emission and their Properties

Type	Identify	Mass (amu)	Charge	Velocity	Penetration
Beta $(\beta, {}_{1}^{0}\mu^{0}e)$	Electron	0.00055	1-	$\leq$ 90% speed light.	Low to moderate depending on energy
Positron $({}_{+1}^{0}\beta,\ +_{1}^{0}e)$	Positively charged electron.	0.00055	1+	$\leq$ 90% speed of light.	Low to moderate depending on energy
Alpha $(\alpha,\ {}_{2}^{4}\alpha,\ {}_{2}^{4}He)$	Helium nucleus.	4.0021	2+	$\leq$ 10% speed of light.	Low
Proton $({}_{1}^{1}\beta,\ {}_{1}^{1}H)$	Proton, Hydrogen nucleus.	1.0073	1+	$\leq$ 10% speed of light.	Low to moderate
Neutron $({}_{0}^{1}n)$	Neutron	1.0087	0	$\leq$ 10% speed of light.	Very high
Gamma $({}_{0}^{0}\gamma)$ ray	High energy electromagnetic radiation such as X- rays.	0	0	Speeds of light.	high

SELF-ASSESSMENT EXERCISE

i. Differentiate between K-capture and L-capture.
ii. What do you understand by the terms fission and fusion?
iii. Write briefly on the types of decay process you know.
iv. Complete the following reaction and calculate the binding energy.

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{131}_{50}Sn + > + 2{}^{1}_{0}n + energy$$

v. Give the properties of particles involved in decay process.

4.0 CONCLUSION

Radioactive decay is therefore a process of transformation of unstable nuclei to stable form through emission of subatomic particles depending on the position of the nucleus on the belt of stability. Fission and fusion are nuclear reactions that involved splitting of heavy nucleus to form light nuclei and coming together of small light nuclei to form heavy nucleus respectively. There are of importance particularly in generating heat energy which can be converted electrical energy.

5.0 SUMMARY

In this unit, you have learnt about:

- the meaning of radioactive decay
- kinetics of decay processes
- the properties of various types of particles involved a decay process
- how to distinguish between nuclear fission and fusion are as well as their importance
- the nature and penetrating capacity of various particles.

6.0 TUTOR-MARKED ASSIGNMENT

i. What is a chain reaction and why is nuclear fission process considered as a chain reaction?
ii. The half-life of ${}^{19}{}_{8}0$ is 30 minutes. What fraction of the isotope originally present would be left after 12 minutes?
iii. The half-life of a sample is 203 minutes.
    (a) How long will it take 95% of the sample to decay?
    (b) How long will it take 99.5% of the sample to decay?

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MODULE 2 NUCLEAR MODELS AND ENERGETIC OF NUCLEAR REACTION

UNIT 1 NUCLEAR MODELS

CONTENTS

1.0 INTRODUCTION

Models are ways of explanation which scientists often used to convey trends in observed behaviours of a particular object or concept. Observed phenomena are used to develop models that are then tested through experiments. It can then afterwards be used to predict the future behavior of such object.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- explain general concept of nuclear model
- describe the principle upon which the models are built
- explain the single particle sheet model
- explain collective nuclei model
- describe the unified model for defining model.

3.0 MAIN CONTENT

3.1 Nuclear Model: General Requirement

In the same way, quantised mode for the atom became the foundation for explaining chemical properties of element and justifying their order in the periodic system; patterns of nuclear stability, result of nuclear reaction at spectroscopy of radiation emitted by nuclei have yield information for the nucleus. In the **nucleus,** there are two types of particles: proton and neutron packed closely together under the influence of two major forces;

i. Electrostatic force
ii. Nuclear force

It is worthy to note that there are many suggestions or proposal on models but no singular nuclear model has been able to explain all about the nuclear phenomena.

3.1.1 Some General Nuclear Properties

It is observed that the binding energy per nucleon is almost constant for the stable nuclei and that; the radius is proportional to the cube of the mass number. This explains or justifies fairly uniform distribution of charge and mass throughout the volume of the nucleus; it also supports the assumption of existence of a strong short range nuclear force.

There is an indication too, that central mass number with Z or N-values 2, 8, 20, 28, 50 and 82 appear more stable. The other uniqueness of these numbers is that if the capturing of neutron or the energy required to release neutron is plotted for different parameters, it will be observed that maxima occurs at these same neutron number just as maxima occur for electronic ionisation energy of the element He, Ne, Ar, Kr, (electron number 2,8,16,32). It shows that some kind of regular substructures exist in the nucleus.

3.1.2 Quantitative Energy Level

The constituents' substructure of neutron and proton with each type of nuclear pairs off as far as possible. The γ – emission from any particle nucleus involves discrete value. It can then be concluded that decay, radioactive nuclei, whether $\propto$, β, or γ involves a transition between discrete quantities energy level.

3.1.3 The Nuclear Potential Well

Imagine a situation when a neutron of low kinetic energy approaches a nucleus. Since the neutron is uncharged, it is not affected by the columbic field of the nucleus; hence more are with no interaction until it is close enough to empower the strong nuclear force. At this point, the neutron experiences strong attraction to the nucleus and is absorbed. When the neutron is absorbed, energy is released and emitted in the form of a gamma- quantum. The energy of gamma γ can be calculated from the known masses of reactants and products nuclides $E_{\gamma} = -931.5$ $(M_{A+1}-M_A - Mn)$. The energy released is the (neutron) binding energy of the nucleus. The total energy of the nucleus has thus decreased. This decrease is called potential well. The exact shape of the well is uncertain (parabolic or square) and depends on the mathematical form assumed for the interaction between the incoming molecule and the nucleus.

3.1.4 Other Requirements (Properties)

There are other properties such as the difference omission for proper understanding of models. Presently, this include rotational energy and angular momentum which is better defined by principal quantum number (n) (which is related to the total energy of the system) and azimuthal quantum number (l) (which is related to the rotational movement of the nucleus). Coupling of spin and orbital angular momentum are also important to the understanding of nucleus model. Various models have been proposed; these shall be considered in the next sub section.

3.2 The Single-Particle Shell Model

It is known that nucleus moves around freely in a nuclear potential well which is spherically symmetric and that the energy of the nucleus varies between potential and kinetic-like harmonic oscillation. For these condition, the solution of the Schrödinger equation says € (nucleon) = $(2U_0/m^2)^6[2(n-1) + l]$

Where U_0 = potential at radius of 20, and m = mass of the nucleus.

The following rules are valid in the potential well which forms the basis to the model.

a. L can have all positive integers the value beginning with 0 and independent of n
b. The energy of the l stage increases n

c. The nucleus enter the level with the lowest total energy independent of whether n or l is the larger
d. There are independent sets of levels for proton and for neutron
e. The Pauli's principle is valid (i.e.) the system can not contain two particles with all quantum numbers by the same
f. The spin quantum number must be taken into account.

3.3 The Collective Nuclear Model

The single particle model assumes that the mass and the charge of the nucleus are spherical. This is true only for nuclei that have distorted shapes. The most common assumption about the description of the nucleus shape is ellipsoidal i.e. cross section of the nucleus is an ellipse Bohr and Mottelson suggested that the nucleus be regarded as a highly compressed liquid undergoing rotation and vibration. Two discrete collective motions can be visualised:

- can imagine nucleus rotates around the y-axis as well as the x-axis
- the nucleus may oscillate between prolate to oblate form (irrotation) as well as vibrate.

Each model of such collective nucleus movement has its own quantised energy. In addition the movement may be coupled. The model allows calculation of rotational and vibration levels.

For example, if ^{238}U is excited above its ground state through interaction with high energy heavy ion (coulomb excitation). Three possible types of excitation are known:

a. Nucleus excitation in which quantum number (J) is charged to raise the nucleus to a higher energy level.
b. Vibrational excitation in which case J is unchanged by the nucleus and is raised to a higher vibrational level characterised by a particular vibrational quantum number.
c. Rotational excitation, also characterised by a particular rotational quantum number. It shows experimentally that rotational levels are more closely spaced and thus transition between rotational levels involves lower energies than de-excitation from excised nuclear or vibrational state.

In the case of even-even nuclei, the rotational energy can be often calculated for the simple expression:

$$€\ rot= (€^2/2I_{rot}\ [n_2(n_r-1)$$

Where I_{rot} is the moment of the inertia as n_r to rational quantum number.

The validity of this quantum depends on whatever the different modes of motion can be treated independently or not which they can for strongly deformed nuclei level ^{238}U.

3.5 The Unified Model for Deforming Nuclei

The collective model gives good description of even-even nuclei, but cannot account for discrepancy between observed spin and the spin value expected from simple particles shell model. This unified model concept has been developed on assumption that a nucleon shell freely in a symmetrical. Potential well, a situation which is valid only for nuclei near closed shells. The angular movement of a odd – odd defined nucleus is due to both the rotational angular momentum of the deformed core and to the angular momentum of the odd nucleon.

Consequently, the energy levels for such a nucleus are different, from those of the symmetric shell models.

Sir S.G. Nilsson calculated odd nuclei: as a function of the nuclear deformationβ. Each shell model level of angular momentum J split into J +1/2 levels (Nilsson).

The Nilsson level are quite different in all characteristics from the shell model state and their prediction of energy, angular momentum, quantum number and other properties agreed better with experimental data for the deformed nuclei than those of any other model.

4.0 CONCLUSION

Various models suggested are attempts to capture the trend in observation of nucleus and its substructure constituents in relation to linear, rotational and vibration motion and their equivalent energy levels.

SELF-ASSESSMENT EXERCISE

i. What do you understand by shell states force and nucleon force?
ii. Describe any two named models you know.
iii. Explain the meaning of the following terms:
   a. Principal quantum number
   b. Azimuthal quantum number.
iv. What do you understand by potential well?

5.0 SUMMARY

In this unit, you have leant about the:

- general concept of nuclear models
- principle upon which the models are built
- single particle sheet model
- collective nuclei model
- unified model for defining model.

6.0 TUTOR-MARKED ASSIGNMENT

i. The observed quadruple moment of ^{59}Co is 0.4 barn
(a) What is the deformation value β (b) What spin value is expected from Nilsson diagram?

ii. Compare and contrast collective nuclear model and the unified model for deforming nuclei.

7.0 REFERENCES/FURTHER READING

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UNIT 2 ENERGETICS OF NUCLEAR RADIATION

CONTENTS

1.0 INTRODUCTION

During a nuclear reaction between atomic nucleus and another atomic particle, three different processes are possible. These are:

(a) nuclear transmutation (in which new nucleus are formed)
(b) inelastic scattering (in which original nucleus are exerted to a higher energy state)
(c) elastic scattering (in which the nucleus remain uncharged). The mass and energy relationship projectiles interact with a nucleus are brought to fore.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- describe the mass-energy relationship when particles and nucleus interact
- explain the various conservation laws as they affect the nuclear reactions
- describe the forms of energy in the three main stages of nuclear reaction.

3.0 MAIN CONTENT

3.1 Conservation Laws in Nuclear Interaction

All conservation laws are applicable in nuclear reactions, these laws are the:

(a) conservation of total energy $\Delta E = 0$
(b) conservation of the linear momentum $\Delta P = 0$
(c) conservation of total change $\Delta Z = 0$
(d) conservation of mass number $\Delta A = 0$
(e) conservation of spin $\Delta I = 0$

Consider Figure 1.2:

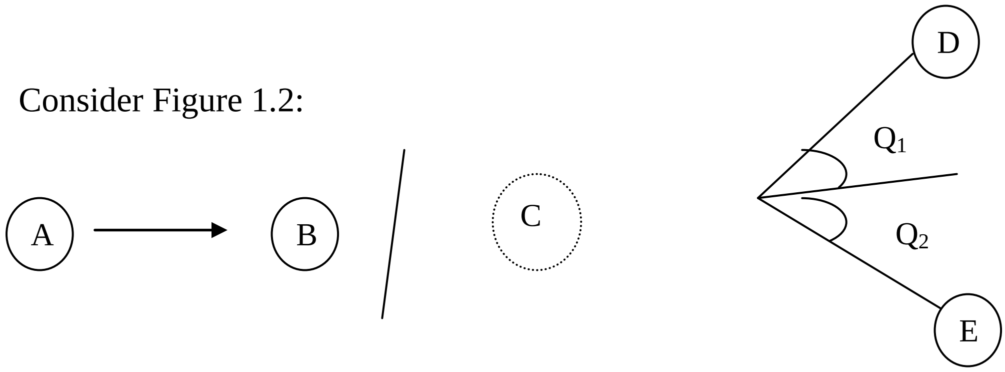

Fig. 1.2: A Projectile showing collision between Objects A and B

M1	M2	Mi	M4
M3			
V1	V2=0	Vi	V4
V3			

This illustrates a projectile in which substance A collide with target atom B, forming intermediate system C. The C system split into product D and E. This is nuclear reaction V_1 is > 0 but V_2 is made to be zero.

3.2 Conservation of Used Energy

$\Delta E = \Delta E$ product - ΔE reactant = 0

Since the linear momentum is a vector quantity,

$$P_1 + 0 = P_3 \text{ Cos } \theta - P_4 \text{ Cos } \theta_4$$
$$P_3 \text{ Sin } \theta = P_4 \text{ Sin } \theta_4$$

Note that some of the laws earlier stated ((d) and (e)) are not always obeyed in high energy reactions in which new elementary particles may be found. Assuming that mass of the particle was independent of its velocity the kinetic energy equation as deduced by Newton:

E_{kin} = ½ Mv^2

3.3 The Mass Energy

For radioactive decay, the energy numeration is given by its Q value.

$$Q \text{ (MeV)} = -931.5\, \Delta m^o$$

Where Δm^o - $M^o{}_3 + Mo_4 – Mi^o – M_2{}^o$

If mass disappears in the reaction ($\Delta Mo < 0$) energy is released, then the reaction is said to be **exoergic** and Q is positive.

For Q < 0 the reaction is **endoergic** as $\Delta Mo > 0$

$E_{kin} = (m – m^o)c^2$ can be separated to five terms if we define:
E^o mass = $M_o\, c^2$ and

$E_{Kaf} = Mc^2$

Then $E_{tot} = E_{kin} + E^o{}_{mass}$

Note also that: $E_{tot} = E_{kin} + E_{pot}$

Hence: $E_{tot} = E_{kin} + E^o{}_{mass} = E_{kin} + E_{pot}$

Therefore; $E_{mass} = E_{pot}$

Where E_{kin} is translational, rotational, vibrational energy and $E^o{}_{mass}$ = mass energy, E_{pot} = gravitational, electrostatic energy, surface energy, chemical binding energy etc.

To have a E_{tot} that include atomic masses in their grounds state E^o mass, the excitation energy of the nucleus above its ground state E_{exc}, the absorption/emission of protons in the reaction E_v and c reaction between charged particles, the electrostatic potential (Coulomb) energy E_{col}, the columb energy must be zero or positive (repulsive). The incoming projective must possess enough kinetic energy to overcome any repulsion. In the process of reaction of repulsion of charged particles, product results in greater kinetic energy.

$E_{tot} = 6_{rm} + 6_{cone} - E^{o}_{MeG} + E_{xec} + E_{r}$

3.4 Elastic scattering

The elastic scattering energy is exchanged between the projectile and the target nucleus but the value of Q is zero. An important elastic scattering reaction is a nuclear reactor involves the slowing down of neutrons from kinetic energies, which they possess when emitted in nuclear fission. The neutrons are slowed down to energies comparable to those of a neutron of gas at the temperature of the material in which they are moving, hence they are known as thermal neutrons.

$$E_{kin} = KT$$

Where E_{kin} is kinetic energy, T is temperature and K is the reaction constant.

The process of slowing down of energetic neutron to low kinetic energies is called moderation.

3.5 Inelastic Scattering

In this group of nuclear reaction called inelastic scattering, part of the kinetic energy of the projectile is transferred to the target nucleus as excitation energy without changing the values of A or Z of either target or projectile . If the projectile is a heavy ion, it may also become excited. However, the collision of the projectile and target nucleus forming the product does result in a value of Q greater than zero.

$$X_1 + X_2 \quad \begin{cases} a \; - \; X_1 + X_2 + \gamma \\ b \; - \; X_1 + X_2^{*} \end{cases}$$

The reaction path (a) indicates that the energy Q is emitted as a γ ray. In the reaction path (b), the Q is retained as excitation energy of the target include.

In case of an inelastic scattering reaction of the formation of an isomer of Ag by the irradiation of ^{107}Ag with neutrons;

$$^{107}Ag\,(n, n') \; ; \quad ^{107m}Ag \longrightarrow \; ^{107}Ag + \gamma$$

As an example of nuclear transmutation consider the following:

$$ {}^{14}_{7}N \quad x \quad {}^{4}_{2}He \rightarrow \left({}^{18}_{9}F\right)^{*} \rightarrow {}^{17}_{18}0 + {}^{1}H $$

$$ \Delta M^{o} = (m_3{}^{o} + m_4{}^{o} - m_1{}^{o} - m_2{}^{o}) $$

Δm^{o} (16.999131 + 1007325 - 14.003074 - 4.002603)

Δm^{o} = 0.001279(u)

3.6 The Compound Nucleus Model

If $E^{o}{}_{kn}$ > E_{cb}, the attractive nuclear force dominate and the particles is absorbed by the target nucleus. Assuming Q > 0, the $E^{o}{}_{mass}$ decreases. This means that, E_{exe} increases and the system is transformed into excited compound nucleus.

Hence, the excitation of the compound nucleus is:

$$ E_{exe} = Q + E^{o}{}_{Kin} $$

SELF-ASSESSMENT EXERCISE

i. What is meaning of moderation
ii. List all conservation laws that are applicable to nuclear reactions.

4.0 CONCLUSION

It is demonstrated enough that conservation laws are all applicable in nuclear reactions. The total amounts of energy remains the same, but keeps changing in the three main stages of nuclear reaction.

5.0 SUMMARY

In this unit, you have learnt that about:

- the conservation laws and how they are applicable to nuclear reaction
- the three phases that make up the nuclear reaction
- elastic scattering
- inelastic scattering.

6.0 TUTOR-MARKED ASSIGNMENT

i. Calculate the mass of an electron accelerated through a potential of 2×10^{8}V.
ii. ^{12}C atoms are used to irradiate ^{239}Pu to produce an isotope of berkelium. What is the coulomb barrier height?
iii. Briefly explain the following:

a. Nuclear transmutation
b. Inelastic scattering
c. Elastic scattering
d. Thermal neutron.

7.0 REFERENCES/FURTHER READING

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MODULE 3 MEASUREMENT OF RADIOACTIVITY

UNIT 1 PRINCIPLE AND MEASUREMENT OF RADIOACTIVITY

CONTENTS

1.0 INTRODUCTION

There is need to device a mechanism that can accurately measure (qualify and quantify) the radioactivity and its effects. This will affect both application of the radioactivity and monitoring its hazards on man and environment. Various types of equipment are employed in the measurement of radioactivity and each makes use of different principles. Each has its limitation which account for preference for others

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- explain the principle underlying the measurement of radiation
- highlight the various methods and instrument used in measuring radioactivity
- state the limitations of those methods used in measuring radioactivity.

3.0 MAIN CONTENT

3.1 Measurement of Radiation

There are so many techniques used for qualitative (detection) and quantitative measurement of individual nuclear properties. This unit discusses these along with the problems associated with the proper sample preparation so as to achieve precision and accuracy.

3.2 Sample Preparation

Samples must be prepared with care and effort must be ensured that it is reproducible if several samples case to be compared. Samples can be prepared in either liquid or solid form.

3.2.1 Liquid Sample

In this form of samples, the emitters are included in the detection system as it ensures high efficiency and reproducibility. Counting of alpha particle and beta emitters are best achieved in liquid sample system.

3.2.2 Solid Sample

These sample techniques can be achieved in variety of ways such as precipitation, evaporation, and electrolysis. The advantage of using solid sample for counting is that, the sample can be made very robust and small, allowing the use of either very simple counting system (e.g. Gieger Muller counter) or the use of commercial counting system. However, care must be taken to ensure uniform thickness solid media.

3.3 Qualitative and Quantitative Measurement

Various techniques and instruments are in vogue when it comes to doing both qualitative (detection) and quantitative measurement.

The detection and counting device are linked together, hence it is worthy to mention that the qualitative and quantitative measurement go on simultaneously.

3.3.1 General Properties of Detector

When a nuclear particle enters detector, it produces excitation and ionisation, both of which can be used for detection. The excitation, if followed by fluorescent de-excitation leads to emission of light which can be registered by light sensitive devices such as photomultiplier tube (PMT) which transform light into an elective current (*i*).

$$I = \frac{\Delta Q}{\Delta t} \qquad \frac{Electric \quad change}{Time}$$

If the current passes through a resistor R, it will produce a voltage pulse.

$$\Delta V = \quad R\frac{\Delta Q}{\Delta t}$$

The pulse is otherwise called signal which can then be quantified.
The following are the techniques and instruments which are commonly used for the measurement of radioactivity.

3.4 Track Measurement

Tracks are formed by nuclear particles in cloud chambers, in solids and in photographic emulsions. The track reveals individual nuclear reactions and radioactive decay processes.

The tracks formed can be directly observed by naked eye in cloud and bubble chambers. However, because of short life span of tracks, it is important to have a permanent record through photography. Tracks measurements are in various forms.

3.4.1 Cloud and Bubble Chambers

This was discovered in 1911. A chamber contains air saturated with vapour. Particles emitted from radioactive substances ionise in air chamber. On cooling to droplet of liquid, these ions condense, leading to production of frog-like tracks which may be photographed.

3.4.2 Solid State Nuclear Track Detector (SSNTD)

The main types of SSNTD are photographic emulsion, crystals, glasses and plastic. Because of high density, nuclear particle can read all KE in these detectors. Nuclear emulsion is similar to optical photographic emulsion. It is used commonly for α particle measurement.

3.5 Gas Counter

The principle of all gas filled counters in ion chambers. The ionisation produced in ion chamber by a single particle is too low to be detected except for alpha particles. However the ion formed are multiplied greatly. Common forms of gas ionisation counter include:

3.5.1 Geiger – Muller Counter

Radiation enters the tube through a thin window. Geiger - Muller counter can detect only β and γ radiations. Note that it is not suitable for α particles because α particles cannot penetrate the wall of window.

3.5.2 Ion Chamber

The ion chamber is a gas – filled space between two electrodes. The electrodes may be two parallel plates have the in another design, cathode act as hollow cylinder and anode acts as a thin wire in its center. The chamber is designed for recording radiation reaching it from outside. It is used to measure β particle or used to measure radioactive sub-particles within it.

3.5.3 Proportional Counter

It is similar to ionisation chamber. The gas multiplication is a function which varies with the applied voltage, and is constant at a given voltage. The detector pulse output is directly proportional to the primary ionisation. Hence, a proportional counter helps to distinguish α and β particles and between identical particles of different energies, once different form of primary ionisation are produced. This technique is also used to detect neutrons.

3.6 Scintillation Detector

Scintillating counting technique was developed in 1908 by Rutherford and Geiger as a reliable method of counting α particles by observing visually the flashes of luminescence produced in a thin layer on ZnS by the α particle. Scintillation optical consist of scintillator or phosphor optically coupled to a photomultiplier tube which produces a pulse of electric current when light is transmitted to the tube from the scintillator. Common forms of scintillator include: gas scintillator, liquid scintillator and solid scintillator.

3.6.1 Gas Scintillator

Several high purity gases are useful scintillator notable N_2, He, Ar, Kr and Xe. Except for N_2, much of the emitted light is in UV range. Therefore, photomultiplier tube that is sensitive to UV must be used or a wave – length shifting gas like N_2 is added.

3.5.2 Liquid Scintillator

This has a wide use for routine measurement of β emitter and can be used for α emitters. The sample is dissolved directly in liquid scintillator solution and a light output measured by photomultiplier tubes. Liquid scintillating counting offers several advantages when measuring low energy β emitters compared to other detectors with problems such as attenuation by detector window, self-absorption and backscattering are avoided. However, introduction of sample into scintillator medium often reduces the light output greatly, a phenomenon known as quenching. The technique also measure α emitter.

3.6.3 Solid Scintillator

Various solid media are used in solid scintillating techniques. Solid scintillator offers a great advantage in measuring virtually, all the emitters. ZnS (Ag) is a traditional phosphor for α detection, while anthrancene and stilbene can be used for β particles detector. NaI with small amount of Tl (NaI(Ti) is a most common phosphor used in measuring γ rays.

4.0 CONCLUSION

Measuring radiations with accuracy and precision is of high importance. Various known techniques and instruments with condition of use have been highlighted. Techniques are selective in terms of the emitters they detect and quantify.

5.0 SUMMARY

In this unit, you have learnt:

- about qualitative and quantitative measurement
- about the general properties of detector
- various techniques and instrument used in measuring sub-atomic particles
- principle and condition underlying the use of various counting system employed in measuring radioactivity.

6.0 TUTOR-MARKED ASSIGNMENT

i. Explain in detail the general conditions and properties of detector used in measuring radioactivity.
ii. What is quenching?
iii. Write short note on scintillating techniques.
iv. Geiger Muller tube remains a very good instrument technique in serving of radioactivity measurement. Discuss.
v. Explain what Track Measurement is.

7.0 REFERENCES/FURTHER READING

Timberlake, K. & Timberlaka, W. (2008). *Basic Chemistry.* Boston: Pearson Educational Inc. Pp. 524 – 538.

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UNIT 2 APPLICATION OF RADIOACTIVITY

CONTENTS

1.0 INTRODUCTION

The modern world has come to witness application of radiation activity of sub-atomic particles and electromagnetic rays in various spheres of human life. This has contributed immensely to the improvement of quality of life. Radionuclei have found application in archeological research, agricultural practices, diagnosis, treatment of various diseases condition and nuclear power reactor etc.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- explain the application of radioactivity in archeological studies
- state the importance of radioactivity to(medical) diagnosis and treatment of diseases
- highlight the principle behind using knowledge of radiation to improve the agricultural practices
- explain how application of radiation of sub-atomic particle helps the nuclear power reaction.

3.0 MAIN CONTENT

3.1 Use of Radionuclide in Archeology/Environmental Studies

Radiological dating is a technique by environmentalist, archeologist, geologist and history to determine the age of artifact is it plants or animals, such as wood, fibres, natural pigment bone and cotton. This is done by measuring the amount of carbon - 14, a natural occurring radioactive form of carbon.

The radioactive carbon – 14 is produced continuously in the upper atmosphere as nitrogen atom captures cosmic ray neutrons.

$$^{14}_{7}N \quad + \quad ^{1}_{0}n \quad \rightarrow \quad ^{14}_{6}C \quad + \quad ^{1}_{1}H$$

The radioactive carbon dioxide $^{14}_{6}CO_2$ is produced from the reaction of $^{14}_{6}C$ with oxygen.

After death, plant uptake of $^{14}_{6}CO_2$ stops.

Carbon-14 undergoes beta decay, the amount of radioactive carbon in the plant material decrease steadily:

$$^{14}_{6}C \quad \rightarrow \quad ^{14}_{7}N \quad + \quad ^{0}_{1}e$$

Researchers use half-life of carbon – 14 (5,730 years) to calculate the length of time, an event (like death of plant take) place. The carbon – 14 techniques is useful only for dating objects less than 50,000 years old. Older object can be analysed studied using K – Ar and U – Pb methods, which are capable of analysing older object since K – 40, Ar – 40 has half-life of 1.3 billion years. Through radiological dating, the age of rocks brought back from the moon by the Apollo mission was found to be about 4 x 10^a year calculate approximately the age calculates for earth.

Example

A piece of wood taken from a cave in New Mexico is found to have a carbon-14 activity (per gram of carbon) only 0.636 times that of wood cut today. What is the age of the wood? The half life of carbon-14 is 5730 years.

Solution from 1st order rate constant for ^{14}C

$$T/_2 \quad = \quad \frac{0.693}{K}$$

$$K \quad = \quad \frac{0.693}{t^{d/_2}} \quad - \quad \frac{0.693}{5730} \quad = 1.21 \times 10^{-4} \text{years}$$

The present ^{4}c active N, is 0.636 time to original activity
$N = 0.630N_o$

We substitute into first* order decay equation

$$\text{Ln}\left(\frac{No}{Nt}\right) = \text{Kt}$$

$$\text{Ln}\left(\frac{No}{0.630No}\right) = (1.21 \times 10^{-4})t$$

Cancel No and solve it

$$\text{Ln}\left(\frac{1}{0.636}\right) = (1.21 \times 10^{-4} \times t$$

$$T = 3.74 \times 10^{3}$$

3.2 Uses of Radioactivity in Agricultural Activities

The use of radiation of sub atomic particles to improve agricultural practices is a major landmark in human endeavour. Absorption of gamma rays helps in eliminating dangerous strain of *Ecoherichia coli* bacteria particularly in red meat. The use of pesticide DDT has been confirmed toxic, to human and animal that is repeatedly exposed to it. This has been effectively replaced by a radiological technique. This is used indirectly to sterilise the males' larva producing no offspring. The food item treated does not carry radioactive rays.

3.3 Industrial Uses

There are many application of radioactivity in industry and engineering. It helps in industries when precision is of importance and required. The flow of liquid or gas through a pipeline can be monitored by injection of a sample containing a radioactive substance. Leaks in pipes can also be detected easily, thereby preserving life.

3.4 Medical Uses

The use of nuclides as radioactive tracers in medicine has been globally acknowledged. A radiation detector can be used to follow the path of the element throughout the body system. Cobalt radiation treatment for cancerous tumor is well known. Solution of Na is injected into bloodstream to follow the flow of blood and locate obstruction to circulatory system.

Thallium – 201 to technetium -99 have been used to survey damage from heart disease. Iodine – 123 concentrate in the thyroid gland, liver and certain part of the brain. This radioactive type is used to monitor goiter and often thyroid problems.

3.5 Scientific Research

The pathway of clinical drug can be investigated using radioactive tracers.

Using labelled radioactive compound like $^{14}CO_2$ helps identify intermediate molecules. Example is photosynthetic process. Labelled $^{14}CO_2$ helps tracing intermediate molecule.

Uranium - 235 is used in binding nuclear power plant includes nuclear research as well as generating energy to drive industries.

SELF-ASSESSMENT EXERCISE

(i) What is meant by radioactive tracers?
(ii) Mention any hazard associated with the use of radioactivity in treatment of agricultural products.
(iii) What are the uses of radionuclide in medical diagnosis?

4.0 CONCLUSION

Radioactivity indeed has come to many important roles in improving the quality of life. It also helps in projecting quality future of well as uncovering the possible medical breakthrough through of good research.

5.0 SUMMARY

In this unit, you have learnt:

- the general application of radioactive
- how to use radiation of isotope preserve agricultural product
- how the knowledge of radioactivity helps in medical diagnosis and treatment
- how to use radioactivity in industry
- the use of radioactivity in scientific research
- how age of artifact is determined by the use of radioisotopes.

6.0 TUTOR-MARKED ASSIGNMENT

i. If the amount of radioactive phosphorus in a sample decreases from 1.5mg to 0.25mg in 28 days. What is the half-life of phosphorus – 32?

(a) The half-life of radioactive decay of calcium -47 is 4.5 days. If a sample has an activity of 1.0μ after 27 days, what is the initial activity of the sample?

(iii) Explain various application of radioactivity in the following:
(a) Medical practices
(b) Dating of artifact
(c) Scientific research
(d) Industries
(e) Agricultural practice.

7.0 REFERENCES/FURTHER READING

Timberlake, K. & Timberlaka, W. (2008). *Basic Chemistry.* Boston: Pearson Educational Inc. Pp. 524 – 538.

Choppin, G. R, Liljenzen J. & Rydbers, J. (2002). *Radiochemistry and Nuclear Chemistry*. Woburn: Butterworth- Heinemann. Pp. 1 – 10.

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UNIT 3 RADIATION HAZARDS

CONTENTS

1.0 INTRODUCTION

Various application of radioactivity is indeed leading to quality improvement in life, as discussed in Unit 2. However, this phenomenon has potential of destroying the same life, it tends to protect. Hazards associated with radiation are discussed in this unit.

2.0 OBJECTIVES

At the end of this unit, you should be able to:

- describe about various sources of radiation exposure
- discuss about the relationship between radiation and health condition
- discuss the management of hazardous nuclear waste
- highlight the ways of protection from radiation exposure.

3.0 MAIN CONTENT

3.1 Exposure to Radiation

Human beings are in constant contact with at least low levels of radiation from natural occurring radioactive isotopes in our homes, office, food, water and air we breathe.

For instance, potassium 40 is present in all potassium containing food $^{14}_{1}$ C, radion-222, strontium-90 and iodine-181 are in various food and air around man.

Cosmic rays is another source of background radiation, people that travel often in air stands the chance of receiving greater amount of cosmic radiation because there are fewer molecules in atmosphere to absorb he radiation.

Medical source of radiation are additional source of radiation exposures. These include dental, X-ray, hip, spine and mammogram. Contact with radiation during research also constitutes another major source. By 1992, approximate 100 radiologists had died of a result of biological radiation damage. Table 6.0 shows average annual radiation receive in U.S.A

Table 6.0: Average Annual Radiation receives by a Person in U.S.A

	Source	Dose (mrem)
Natural	The ground	20
	Air, water, food	30
	Cosmic rays	40
	Wood, concrete, break	50
Medical	Chest – ray	20
	Dental- x ray	20
	Mammogram	40
	Hip x – ray	60
	Lumbar some x-ray	70
	Upper gastrointestinal X-ray	200
Others	Television	20
	Air travel	10
	Radon	200m
* Varies wisely		

Mrem = milli radiation equivalent in man

3.2 Radiation and Health disorders

The biological effect of very large whole body doses leads to radiation sickness and early death while large organ doses leads to local cell destruction, and possibly organ death. Exposure to radiation greater than 100 rem (rem is the measure of radiation), the person may suffer the symptoms of radiation sickness: nausea, vomiting, fatigue and reduction in white blood cell count. At dosage greater that 300 rem all white blood cells get destroyed, the victim suffers diarrhea, hair loss and other infection while at 500 rem, half of the population dies; hence it is called LD_{50} (Lethal dose for one half the population). Table 7.0 shows function LD_{50} for various life forms. Dosage above 600 leaves all humans fatal within a week.

Table 7.0: Lethal Dose (LD_{50}) for different Life Form

Life	*formD_{50} (rem)*
Insect	**100,000**
Bacterium	**50,000**
Rat	**800**
Human	**500**
Dog	**300**

* Radiation equivalent in human

The earth we live is drenched in radiation from cosmic sources and mineral exploration from the ground. Therefore, the effects of the natural radiation background has become an important health issue particularly radon levels in houses. Also related closely to this is the effect of man-made sources of similar low levels, such as nuclear waste. Basically, when it comes to the effect of radiation on human cell, two types of cells come into mind: those that directly involve in functioning of the organ (e.g. bone marrow, liver, or the nervous system) and those which are associated with reproductions. Radiation damages in the former give rise to somatic effect such as cancer induction and to later, a genetic effect.

Exposure to large dose radiation can occur by:

Accidental exposure e.g. Japan, Chernobyl: This exposure is said to be stochastic because the harm caused is statistically distributed over the exposed population. The frequency of tumor induction is observed to increase linearly with the dose.

Deliberate exposures: these are deterministic because the damage is caused intentionally to a certain organ or population. Such irradiations are considered to have a threshold value, below which no effects occur.

3.3 Management of Radioactive Waste

Handling of radiation waste is a major source of radiation in the community. Nuclear power system remains the cheapest, source of power to drive industries and electricity, however, the hazard it generates if the waste is not properly disposed is overwhelming. Countries that involve in nuclear power generation dispose the nuclear power waste through large water bodies such as ocean and seas.

However, the hazardous effect from those waste only come back to man with time, as shown in the Figure 1.3.

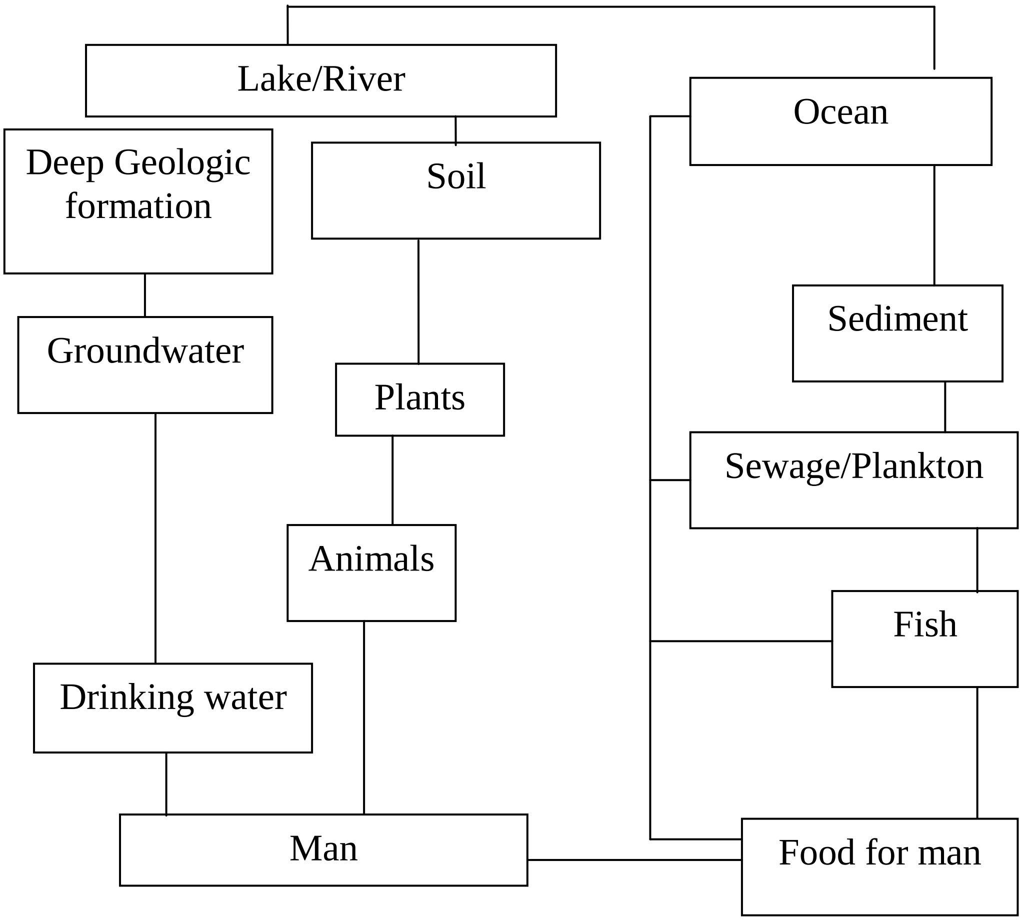

Fig. 1.3: Fate of Hazardous Contaminants in an Ecosystem

Early 1990, the Environmental Pollution Agency gave its approval for the storage of radioactive hazardous waste in chambers 2150 ft underground. That was implemented in 1999 when waste isolation pilot plant (WIPP) marked repository site in New Mexico to receive plutonium waste from former U. S. Bomb factories.

However, despite the U.S authority assured the populace the safety of such scheme, the mean of transporting such waste to site has been another (problem) source of radiation, should the nuclear waste be transported through the rail or by highway truck?

Another safer method of handling hazardous nuclear waste as proposed in the wake of various criticism over dumping nuclear waste in either deep sea or buried deep underground, include casting the nuclear waste into ceramics to eliminate the possibility of waste dissolving in ground water.

The encapsulated waste could then be deposited in underground salt drone. Salt drones are located in geographically stable areas that has held petroleum and compressed natural gas trapped for millions of years. Another method involves storing long-lived radionuclide from spent fuel underground in a heavy, shock – resistant container until they have decayed to the point they are no longer biologically harmful. Example include strontium - 90 (half-life = 28years) and plutonium – 298 (half-life = 24000 years) must be stored for 280 years and 240,000 years respectively before they lose 99.9% activities. However the problem of corrosion of container is another point the critics argued for picking holes in the method.

3.4 Protective Measure from Radiation Laboratory Work

Three basic principles are recommended for keeping radiations exposure to a minimum level; these are:

(i) Shielding
(ii) Control
(iii) Distance.

If a radiochemical laboratory is designed properly and the work is performed in such a manner that the general background contamination is sufficiently low so as to avoid low level tracer, then the health aspect of radiation control are satisfied. The general principles are:

1. special room/location is used for radioactive work
2. the airborne contamination must be prevented in the laboratory
3. the air velocity in the hood should never be below $0.5m^{s-1}$
4. limitation of radioactive work to a minimum area
5. the room should be equipped with alarm system to monitor hazards such as interrupted water system
6. entering and leaving the f laboratory should be through air locked and hand as well as feet must be sensored for radioactivity
7. shielded cells are used which helps to keep the pressure low than that for the working pressure.

3.5 Control of Radiation Protection Measure

In larger organisations, protection of radiation measure three stages:

(i) **Prevention** – This includes the use of devices such as fume hoods, α boxes, radiation shielding, tongs etc.
(ii) **Supervision** stage involves the use of radiation instrument to monitor radiation level. For instance, small TLD, film or pocket pen dosimeter is used for individual monitoring. For spills and

contamination of hand and shoes, special contamination instrument (counters) are used which are more sensitive than the monitoring dose instrument.

The **after control** usually consists of checking personal dosimeter and a medical examination. This may be depending on the type, and level of work executed. The dosimeter may be checked, twice a week or a month, while examination may be once or several times a year.

SELF-ASSESSMENT EXERCISE

i. Discuss briefly what is meant by accidental exposure and deliberate exposure to radiation.
ii. What is LD_{50}?

4.0 CONCLUSION

The use of radioactive isotope can indeed have negative consequences if adequate steps are not taken into cognizance. The methods of nuclear waste disposal remain a great source of radiation. However, shielding oneself will go a long way in curbing individual exposure to the radiation.

5.0 SUMMARY

In this unit, you have learnt about:

- various ways through which man can be exposed to radiation
- various health disorders that exposure of hazard radiation can cause
- types of exposure
- how nuclear waste are being handled
- methods of protecting radiation exposure.

6.0 TUTOR-MARKED ASSIGNMENT

i. Briefly discuss the method involved in management of radioactive waste.
ii. Explain what is involved in protecting man and environment from radiation exposure.
iii. Certain diseases are direct or indirect consequences of radiation exposure. Explain.
iv. At radiation dosages beyond LD_{50}, man stands the risk of extinction. Discuss.
    a. What is radiation protective measure all about?

7.0 REFERENCES/FURTHER READING

Timberlake, K. & Timberlaka, W. (2008). *Basic Chemistry.* Boston: Pearson Educational Inc. Pp. 524 – 538.

Choppin, G. R, Liljenzen J. & Rydbers, J. (2002). *Radiochemistry and Nuclear Chemistry*. Woburn: Butterworth- Heinemann. Pp. 1 – 10.

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