DEPARTMENT OF EDUCATION

GRADE 12

PHYSICS

MODULE 5

RADIOACTIVITY AND NUCLEAR ENERGY

PUBLISHED BY FLEXIBLE OPEN AND DISTANCE EDUCATION
PRIVATE MAIL BAG, P.O. WAIGANI, NCD
FOR DEPARTMENT OF EDUCATION
PAPUA NEW GUINEA
2017

Writers
Lembias Magasu

Content Editors
Science Department
Subject Review Committee

Language Editor
Dr. Mirzi. L. Betasolo

Course Format Editor
Elizabeth. W. Aimundi

GRADE 12

PHYSICS

MODULE 5

RADIOACTIVITY AND NUCLEAR ENERGY

IN THIS MODULE, YOU WILL LEARN ABOUT:

12.5.1:	**RADIATION**
12.5.2:	**RADIOACTIVITY**
12.5.3:	**NUCLEAR ENERGY**

Acknowledgement

We acknowledge the contribution of all Lower and Upper Secondary teachers who in one way or another helped to develop this Course.

Our profound gratitude goes to the former Principal of FODE, Mr. Demas Tongogo for leading FODE towards this great achievement.

Special thanks are given to the staff of the Science Department of FODE who played active roles in coordinating writing workshops, outsourcing of module writing and editing processes involving selected teachers of Central Province and NCD.

We also acknowledge the professional guidance and services provided through-out the processes of writing by the members of:

Science Subject Review Committee-FODE
Academic Advisory Committee-FODE
Science Department- CDAD

This book was developed with the invaluable support and co-funding of the GO-PNG and World Bank.

DIANA TEIT AKIS
Principal-FODE

Flexible Open and Distance Education
Papua New Guinea

Published in 2017

Printed by the Flexible, Open and Distance Education
ISBN 978-9980-89-568-4
National Library Services of Papua New Guinea

TABLE OF CONTENTS

Page

SECRETARY'S MESSAGE

Achieving a better future by individual students, their families, communities or the nation as a whole, depends on the kind of curriculum and the way it is delivered.

This course is part of the new Flexible, Open and Distance Education curriculum. The learning outcomes are student-centred and allows for them to be demonstrated and assessed.

It maintains the rationale, goals, aims and principles of the National Curriculum and identifies the knowledge, skills, attitudes and values that students should achieve.

This is a provision by Flexible, Open and Distance Education as an alternative pathway of formal education.

The Course promotes Papua New Guinea values and beliefs which are found in our constitution, Government policies and reports. It is developed in line with the National Education Plan (2005 – 2014) and addresses an increase in the number of school leavers affected by lack of access into secondary and higher educational institutions.

Flexible, Open and Distance Education is guided by the Department of Education's Mission which is fivefold;

- To develop and encourage an education system which satisfies the requirements of Papua New Guinea and its people
- To establish, preserve, and improve standards of education throughout Papua New Guinea
- To make the benefits of such education available as widely as possible to all of the people
- To make education accessible to the physically, mentally and socially handicapped as well as to those who are educationally disadvantaged

The College is enhanced to provide alternative and comparable path ways for students and adults to complete their education, through one system, two path ways and same learning outcomes.

It is our vision that Papua New Guineans harness all appropriate and affordable technologies to pursue this program.

I commend all those teachers, curriculum writers, university lecturers and many others who have contributed so much in developing this course.

UKE KOMBRA, PhD
Secretary for Education

MODULE 12. 5 Radioactivity and Nuclear Energy

Introduction

Radioactivity is the result of processes or activities in the nucleus of an unstable atom. Such atoms are unstable because of the unbalanced number of protons and neutrons in their nucleus. The number of protons is usually fixed for atoms of different elements. However, in atoms of some elements there is surplus or fewer neutrons. Since the number of protons and neutrons are not balanced in some atoms, they become unstable. At any instant in time their nucleus will react to reach a stable condition. This process is known as radioactive decay.

Radioactivity involves the decaying process taking place in the nucleus of an atom emitting radioactive rays or particles. The period during which the atomic disintegration reduces to half the original count is called a half-life. If stable condition is not fully achieved the decaying process will continue until stable condition is achieved, usually forming completely new daughter elements.

It is well documented and expected that high levels of radiation have been recorded near and around nuclear reactor power stations. This is the reason why radiation safety and the use of radiation shields in nuclear reactors are of paramount importance.

As the nucleons are held by a huge amount of force in the nucleus, there must be a release of enormous amounts of energy during the radioactive decay process, where the formation of daughter elements and stability is reached. The decaying process continues until stability is reached. Neutrons produced during nuclear fission reactions split other heavy atomic nuclei producing more neutrons, repeating the process and thus resulting in a chain reaction. The release of energy in this process is the basic principle of producing energy for the nuclear reactor power stations and nuclear weapons. When a chain reaction is not controlled it is called an atomic bomb and when it is controlled or moderated it becomes a nuclear reactor that result in both useful and deadly by-products.

Nuclear reactor power stations that are currently in many countries utilise the energy released during nuclear fission. Nuclear reactors are not only used to generate power, but are also used for research purposes.

A mushroom cloud produced by an atomic bomb which is an uncontrolled nuclear reaction.

There are two types of nuclear reactors. The fusion reactor releases energy when two light atoms are forced to merge into one and the fission nuclear reactor splits heavier atoms into lighter atoms.

The meltdown of nuclear power stations in Russia (Chernobyl) and Japan (Fukushima) has shown in no uncertain terms that researches into radiation protection and safety are of paramount importance in the operations of nuclear reactor power stations.

Learning Outcomes

After going through this module, you are expected to:

- define wave.
- differentiate wave types.
- generate waves using ropes and springs.
- describe the difference between transverse and longitudinal waves in terms of particle motion.
- differentiate mechanical and electromagnetic waves.
- give examples of transverse and longitudinal waves.
- apply mathematical formulae in determining wave properties which include amplitude, wavelength, period and frequency.
- describe relationship between frequency and period from

$$T = \frac{1}{f}$$

- draw wave diagrams from given parameters .
- demonstrate that waves are in phase or out of phase with respect to a reference wave.
- describe when two waves interfering constructively or destructively when they come together.
- apply mathematical formulae to calculate unknown quantities of a given wave using the wave equation:

$$v = f \times \lambda = f\lambda$$

- explain what light is in terms of waves.

Snell's Law: $\frac{n_1}{n_2} = \frac{\sin r}{\sin i}$ or $n_1 \sin i = n_2 \sin r$

- demonstrate an understanding of practical applications of
    i) total internal reflection in periscopes, prisms, optic fibres and endoscope just to name a few.
    ii) effect of refraction; determining real depths and apparent depths of objects underwater.
- research and recognize that sound energy can be transmitted by waves through solid, liquid and gases.

Time Frame

Suggested allotment time: **10 weeks**

This module should be completed within 10 weeks.

If you set an average of 3 hours per day, you should be able to complete the module comfortably by the end of the assigned week.

Try to do all the learning activities and compare your answers with the ones provided at the end of the module. If you do not get a particular question right in the first attempt, you should not get discouraged but instead, go back and attempt it again. If you still do not get it right after several attempts then you should seek help from your friend or even your tutor.

DO NOT LEAVE ANY QUESTION UNANSWERED.

12.5.1 Radiation

The term **radiation** refers both to the transmission of energy in the form of waves, and the transmission of streams of atomic particles through space.

The radiation we will be studying now is called **nuclear radiation**. It is caused by activities within an unstable nucleus of an atom. An unstable atom has an unbalanced number of protons and neutrons in its nucleus. Therefore, at some stage the nucleus will release energy by emitting radiation while trying to attain a more stable position.

Inside an Atom

In our studies in science, we have learnt that matter is made up of atoms. We also learnt that the structure of an atom is made up of a **nucleus** that contains particles called **protons** and **neutrons**. Protons and neutrons are collectively referred to as **nucleons**. Outside the nucleus is a cloud which contains **electrons**.

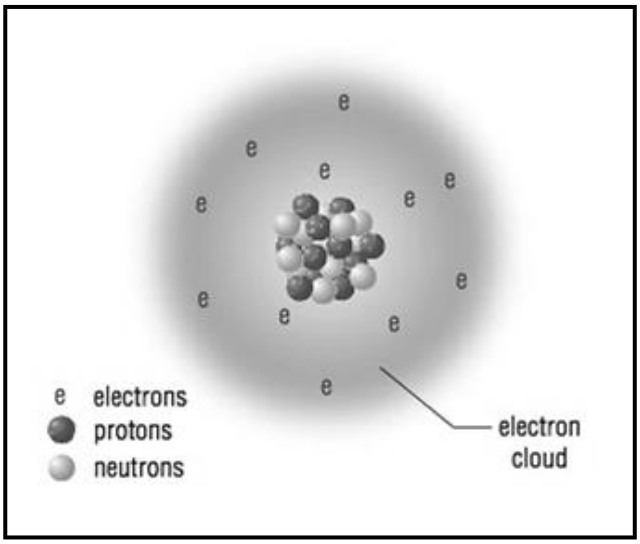


Figure 1 An atom with a small nucleus surrounded by an electron cloud.

Modern atomic theory suggests an atom with a small nucleus surrounded by an electron cloud. The illustration in figure 1 however, gives a false impression of the size of the nucleus. The neutron has zero charge and the proton is positively charge, while the outer particle, the electron is negatively charged. In this module, we will focus our study on the nucleons.

The table below summarizes the properties of these three (3) main particles.

Atomic particle	Location in an atom	Mass	Charge	Symbol
Proton	Nucleus	1.673×10^{-27} kg	$+1.6 \times 10^{-19}$ C	${}^{1}_{1}p$
Neutron	Nucleus	1.675×10^{-27} kg	zero	${}^{1}_{0}n$
Electron	Outside the Nucleus	9.109×10^{-31} kg	-1.6×10^{-19} C	${}^{0}_{-1}e$

Table 1 Properties of the main atomic particles.

Isotopes

Atoms of the same element with different numbers of neutrons are called **isotopes** of that element. Many isotopes occur naturally, but some are made artificially.

The number of protons in the nucleus is called the **atomic number**, while the total number of nucleons is called the **mass number**. On the periodic table, each element is represented as shown below.

An element with symbol **X**, mass number **A** in the **unified atomic mass unit** (**u**) and atomic number **Z** is given with the following symbol.

$$ {}^{A}_{Z}\mathbf{X} $$

The number of protons is given by Z.

The number of electrons is also given by Z since an atom is electrically neutral.

The number of neutrons (**N**) in this atom is given by **N = A – Z**.

Example 1 An isotope of the element fluorine (F) is given with the symbol below.

$$ {}^{18}_{9}\mathbf{F} $$

Determine the number of protons, neutrons and electrons in this isotope.

Solution

Mass number A = 18, Atomic number Z = 9,

The number of protons = Z = 9

The number of neutrons N = A – Z = 18 – 9 = 9

The number of electrons = Z = 9

For example, hydrogen exists naturally in three forms, each with one proton and differing number of neutrons. The isotopes of hydrogen are Hydrogen, Deuterium and Tritium.

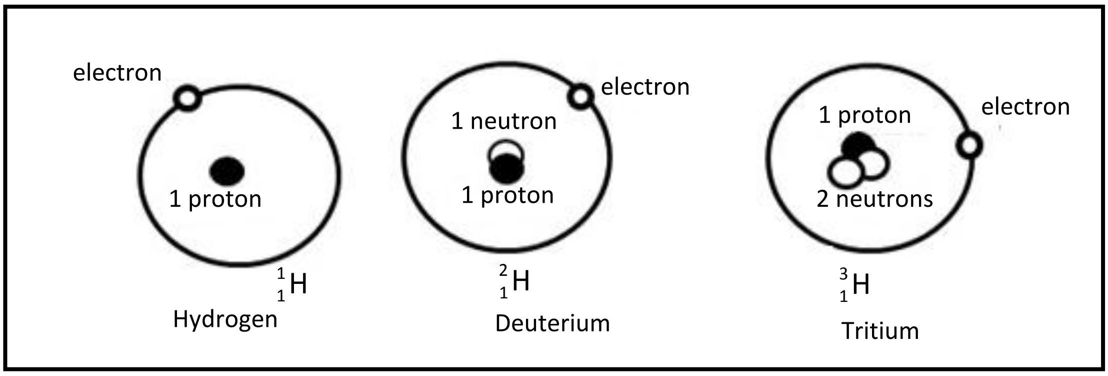


Figure 2 Isotopes of hydrogen, each with one proton and one accompanying electron

Nuclear stability

In most of the naturally occurring elements, the number of protons is approximately the same as the number of neutrons in the nucleus. These atoms are stable. The stability of an atom depends on the ratio of protons to neutrons. As the atomic number increases, the ratio of neutrons to protons needed for stability also increases.

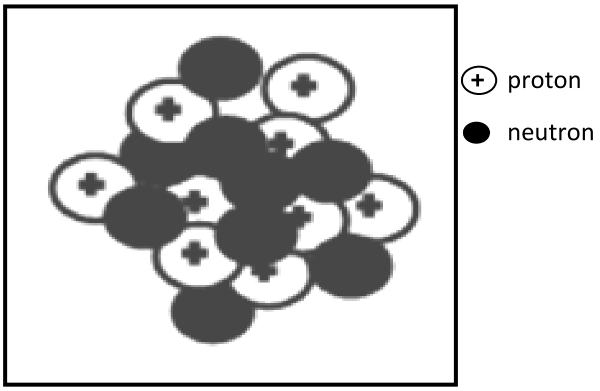


Figure 3 Stable nucleus of an atom of fluorine-18 (${}^{18}_{9}F$ with 9 protons and 9 neutrons)

Many elements, whose nuclei have too few or too many neutrons, are unstable and undergo **radioactive decay** in which they change and emit **radiation**. The type of radiation that is emitted depends on the nature of the decay.

Now check what you have just learnt by trying out the learning activity on the next page!

Learning Activity 1

10 minutes

Answer the following questions on the spaces provided.

1. Define the following terms.

   a) Nucleon

   b) Isotope

   c) Nuclide

2. Determine the number of protons, and electrons for each of the following isotopes.

ISOTOPE	Number of protons	Number of neutrons	Number of electrons
${}^{14}_{6}\text{C}$			
${}^{93}_{38}\text{Sr}$			
${}^{216}_{84}\text{Po}$			
${}^{228}_{88}\text{Ra}$			
${}^{241}_{95}\text{Am}$			

3. Give a reason why the nuclei of some isotopes are unstable.

Thank you for completing learning activity 1. Now check your work. Answers are at the end of the module.

Main Types of Nuclear Radiation

Nuclear radiation results from an unstable nucleus. Radiation from the nucleus can be in the form of energetic particles or electromagnetic waves. The three main types of nuclear radiation are **alpha (α)**, **beta (β)** and **gamma (γ).**

Alpha radiation (α)

Alpha radiation is a particle emission that occurs only in elements of high atomic weight. An alpha particle is the same as a helium nucleus and consists of two protons and two neutrons. Because alpha particles have two protons, it is positively charged.

Alpha particles travel at about 5% of the speed of light. They cause intense **ionisation** due to their +2 charge. When they collide with matter, alpha particles slow down, transferring their kinetic energy to the other molecules, shaking many of them apart and leaving a trail of positive and negative ions behind them.

Alpha particles have low power of penetration, travelling only a few centimetres in air. They can be stopped by a sheet of thick paper. Alpha particles can be detected on a photographic plate in a cloud chamber and by a spark counter. Only the most energetic can be detected on a Geiger-Müller counter. Americium-241 is a good laboratory source of alpha radiation.

Beta radiation (β)

Beta radiation is another type of particle emission that occurs in unstable nuclei. Beta particles are of two types, **negatrons** (**electrons, $^{0}_{-1}e$, β^-**) which are negatively charged and **positrons** (**$^{0}_{+1}p$, β^+**) which are positively charged.

Isotopes with excess neutrons may decay into a more stable form by the conversion of a neutron into a proton, with the concurrent emission of a negative beta particle. An electron represented as, e^- or $^{0}_{-1}e$, emitted from the nucleus is called a beta particle (β-particle). An electron has 1/1836 or 0.05% of the mass of proton therefore its atomic mass number can be taken as zero (0) and an atomic number of –1.

Isotopes with excess protons may become more energetically stable by positron (positive beta particle) emission where a proton is converted to a neutron with the concurrent emission of a positron. A positron e^+ or $^{0}_{+1}e$,, has the same properties as an electron except that it is positively charged.

Beta particles (both positrons and negatrons) move at high speeds ranging from 0.3 to 0.99 times the speed of light ($3 \times 10^8 ms^{-1}$). Because of their speed and being small, they are more penetrating than alpha particles and can travel about 1m in air before slowing down to become just like the surrounding electrons. They can be stopped by a sheet of aluminium. Beta particles can be detected on a photographic plate, in a cloud chamber (thin and twisted tracks) and by a Geiger counter.

Gamma radiation (γ)

Gamma radiation is the only type of nuclear radiation that is an electromagnetic (em) wave. An electromagnetic wave occurs as **photons** or **rays**. They have a very high frequency and a very short wavelength. Gamma radiation most often results in concurrence with beta emission. However, some nuclides decay by gamma ray emission alone.

Gamma rays travel at about the speed of light (3×10^8m/s) and have no net charge. Gamma rays are very penetrating, but their ionising power is very low. They are never completely absorbed but their intensity can be reduced significantly by several centimetres of lead.

Properties of Nuclear Radiation

Ionizing ability of nuclear radiation

Nuclear radiation has the ability to cause other molecules and atoms to become ions. This is referred to as **ionisation**. Ionisation can occur when molecules gain electrons and become negative ions or when they lose electrons and become positive ions.

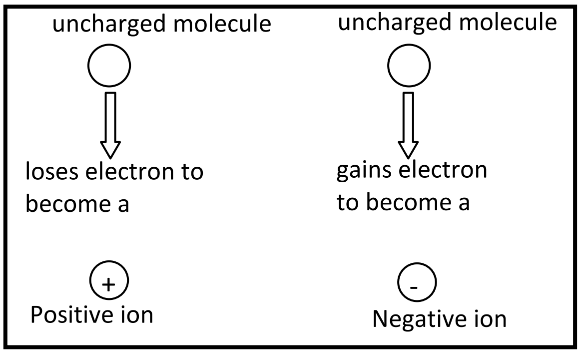


Figure 4 Two ways of ionisation

Any particle or electromagnetic radiation that can cause atoms or molecules to become ions is called **ionizing radiation**.

Alpha radiation has the highest **ionizing ability**, this is followed by beta radiation and then gamma radiation. Alpha radiation with energy of about 0.32 pica-joules (10^{-12}) can produce about 10 000 ion pairs (positive and negative ions) per millimetre along its path. Beta radiation with the same amount of energy produces about 100 ion pairs per millimetre. Gamma radiation with the same amount of energy will produce about 1 ion pair per millimetre.

Nuclear radiation is ionizing radiation and it can produce harmful effects in organisms. When molecules in body tissue become ionized they can result in the growth of **cancer** cells. Many of the pioneering scientists in the field of nuclear physics died of **leukaemia** and **thyroid cancer**.

The ionizing ability of nuclear radiations is also widely used in medicine for diagnosing as well as treating certain diseases. Certain industries and scientific research fields also make extensive use of the ionizing ability of nuclear radiation.

Effects of electric fields and magnetic fields on nuclear radiation

When a radioactive source that emits all three kinds of radioactivity is directed into a magnetic or an electric field, the three radiations behave differently, as shown in figure 5. Their behaviour is explained by the type of charge that each radiation has.

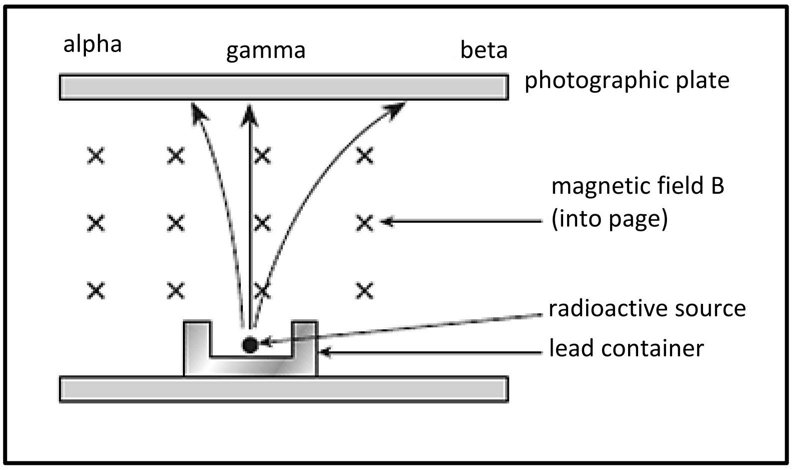


Figure 5 Deflection of alpha, beta and gamma rays by a magnetic field.

It was found that the alpha radiation is attracted towards the negative plate of the electric field. The beta radiation is attracted towards the positive plate, while the gamma radiation is unaffected and passes straight through.

This shows that alpha radiation has some kind of positive charge, beta, a negative charge, while gamma has no charge associated with it.

The deflections of these radiations in a magnetic field support this. In a magnetic field, alpha particles are deflected only by a small amount because they are more massive than beta particles. Gamma rays are not deflected at all.

The directions of alpha and beta radiation can be determined using the **right hand (slap) rule** or **Fleming's left hand rule** as shown in figure 6 on the next page. These two rules are used to determine the force on a charge in a magnetic field. When applying both rules to this case, always consider alpha radiation as a current in order to determine the direction of force on the alpha radiation. Beta radiation will always be opposite to the direction of alpha radiation. Gamma radiation in all cases passes through a magnetic field without any change in direction.

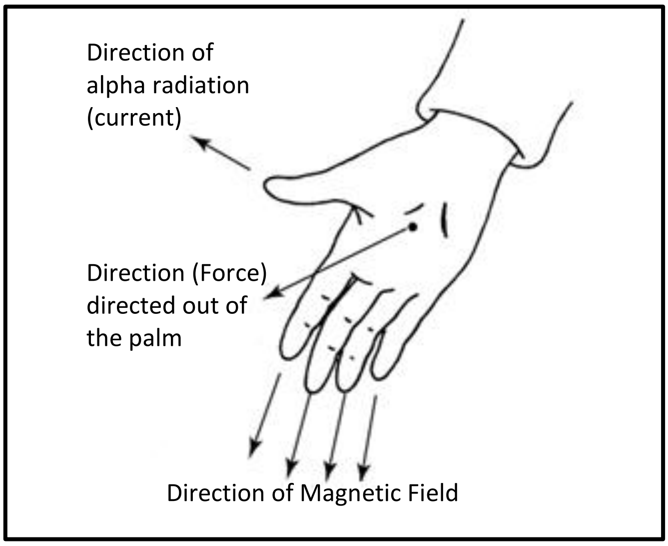
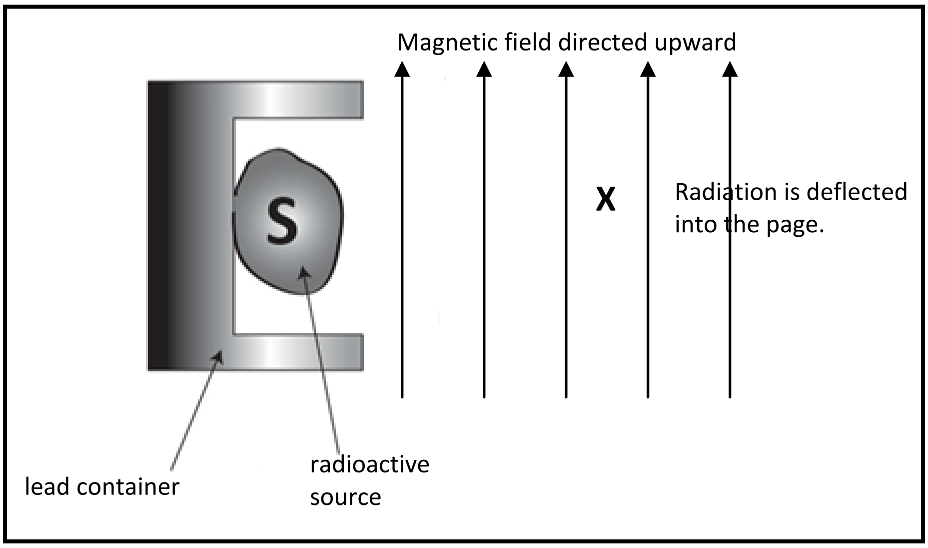


Figure 6 Right hand (slap) rule showing the direction of deflection of α radiation

Example 2

A radioactive source **S** was placed near a magnetic field directed upward. The radiation that was emitted by **S** was deflected such that it was directed into the page (as shown by the **X**).



What type of radiation was emitted by **S**?

Solution

If we use the right hand (slap) rule and Fleming's left hand rule, the direction of the current would be towards the left for the force to be directed into the page. The radiation from **S** passes from left to right, therefore the radiation cannot be positive but it must be negative. We can conclude that this radiation is beta (negatron) radiation.

Penetration power of nuclear radiation

Penetration power is a measure of the strength of a radiation particle or ray. It is sometimes described by how certain materials absorb these radiations. The penetrative power of the three (3) main types of radiation is shown in figure 7 below.

Alpha radiation can pass through several centimetres of air before being absorbed. A piece of paper is also enough to absorb alpha radiation.

Beta radiation is more penetrative. It can pass through the body as well and is best absorbed by a sheet of metal.

Gamma radiation is the most penetrative radiation and is never fully absorbed. Several centimetres of lead is needed to absorb gamma rays.

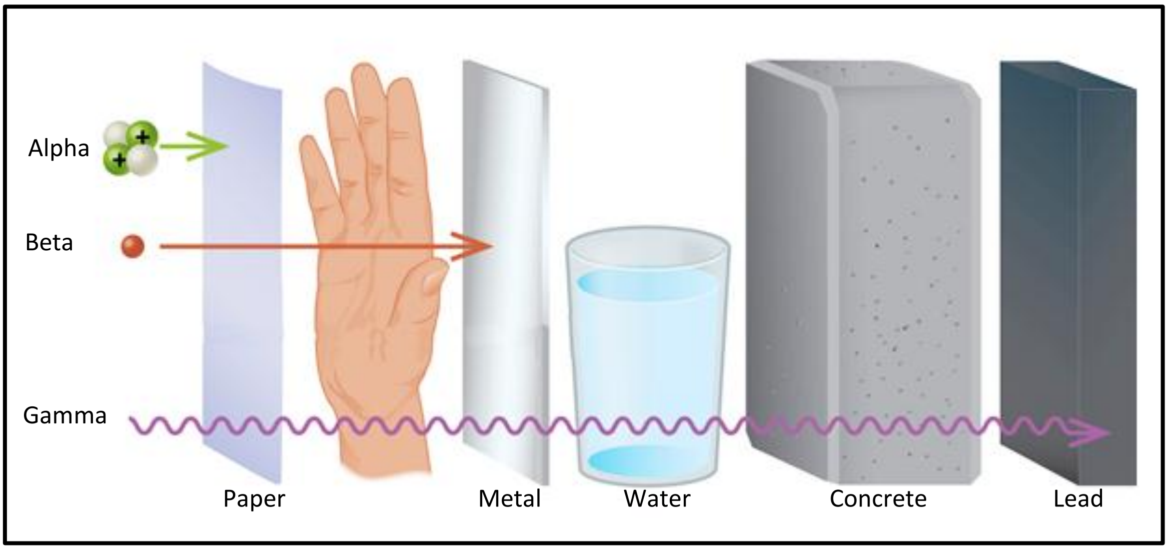


Figure 7 The penetrating ability of different forms of radiation.

The penetration powers of radiation are important properties that are considered when dealing with sources of radiation. Depending on the type of radiation that is used, scientists and persons who deal with radioactive substances have to be properly protected.

Below is a summary of the properties of the main types of radiation.

Radiation	**Alpha**	**Beta**	**Gamma**
Symbol	α, ${}^{4}_{2}\alpha$, ${}^{4}_{2}\mathrm{He}$	β^{-}, ${}^{0}_{-1}e$, ${}^{0}_{-1}\beta$	γ , ${}^{0}_{0}\gamma$
Type	Particle	Particle	Em wave
Mass	4u	0.0005u	none
Charge	+	-	none
Speed	5% to 10% of the speed of light	95% of the speed of light	Speed of light
Ionizing ability	Strong	Weak	Almost none
Penetration Power	A few cm of air	A few mm of metal	Many cm of lead
Deflection by Magnetic and Electric field	Yes	Yes	No
Detection	Causes strong fluorescence Affects photographic film	Causes fluorescence Affects photographic film	Causes weak fluoresecence Affects photographic film

Table 2 Summary of the properties of the main types of radiations

Ways of detecting nuclear radiation

The properties of radiation listed in the previous section allow us to design instruments that can detect radiation. Detecting radiation is very important due to the harmful effects that radiation has on people. By being able to detect radiation, we can avoid potentially dangerous situations when handling radioactive materials.

Photographic papers

Photographic papers obviously can be used to detect radioactive rays. They are blackened by the rays even though they are completely shielded from light. Scientists working on radiation are required to wear a sealed badge containing a photographic film. The film is replaced and developed at regular intervals of time and the amount of blackening of the film indicates the level of exposure to radiation. If the level is too high, the worker must be checked by a doctor and the area checked for leakage of radiation. There is a standard limit as to how much radiation a worker can be exposed to during a year.

Scintillation counter

One of the early methods of detecting radioactivity was with the use of a fluorescent screen in conjunction with a microscope. When radioactive rays struck the screen, light spots or scintillations were produced. The modern scintillation counter consists of a fluorescent crystal placed in contact with a photomultiplier. When radioactive rays strike the crystal, light is emitted. The light is detected by the photomultiplier and its electronic circuit. Such a counter is much more sensitive than a simple fluorescent screen.

Electroscope

Some radioactive rays can also discharge a charged electroscope. The radiation from the radioactive source ionizes the air surrounding the charged electroscope.

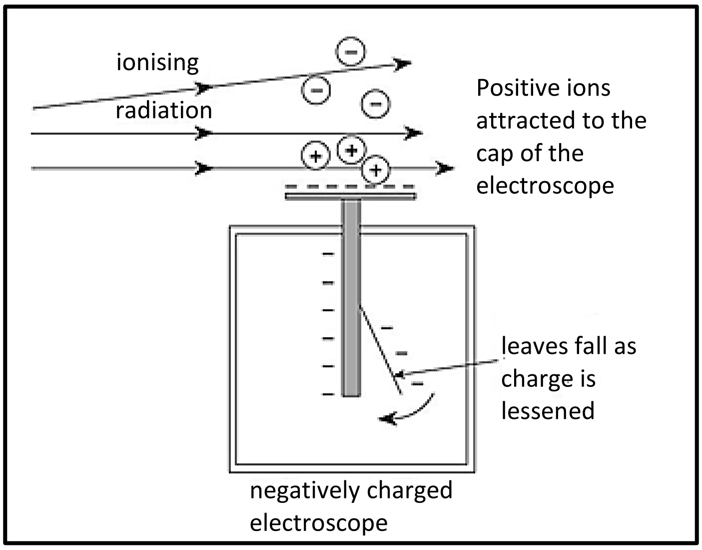


Figure 8 An electroscope detects ionised air particles from ionizing radiation

.

Spark counter

A spark counter is another device used to detect radioactivity. When radioactive rays pass between a positively charged wire grid and a negatively charged metal plate, ionization occurs. The ions and electrons produced enable a large current to suddenly pass through the air under the high voltage between the grid and the plate. A spark can be seen and heard or it may be registered by an electronic device (such as a scaler).

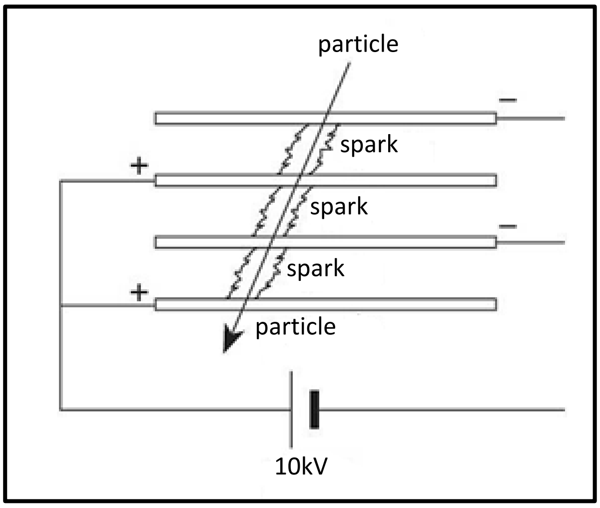


Figure 9 Radiation passing through a spark counter creating ions which result in sparks

Geiger-Müller Tube

The Geiger-Müller (GM) tube is one of the most important instruments for detecting radiations. It also makes use of the ionization effect. When radioactive rays enter the GM tube, a sudden large current pulse passes through the tube. This pulse can be detected by a scaler or rate-meter. A scaler records the total number of counts per second. The GM tube and a scaler or rate-meter are usually referred to as a Geiger counter.

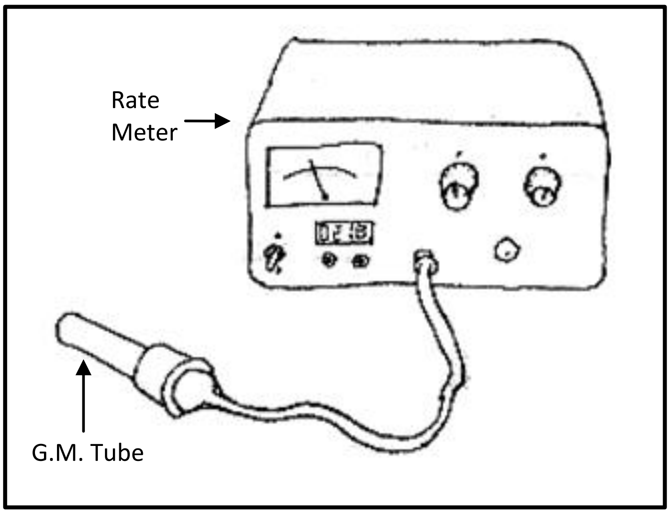


Figure 10 An illustration of a GM tube and counter which is commonly used to detect radiation

Diffusion cloud chamber

A diffusion cloud chamber is used in some laboratories to detect radioactivity. The base of the chamber is cooled by dry ice to about -40°C.

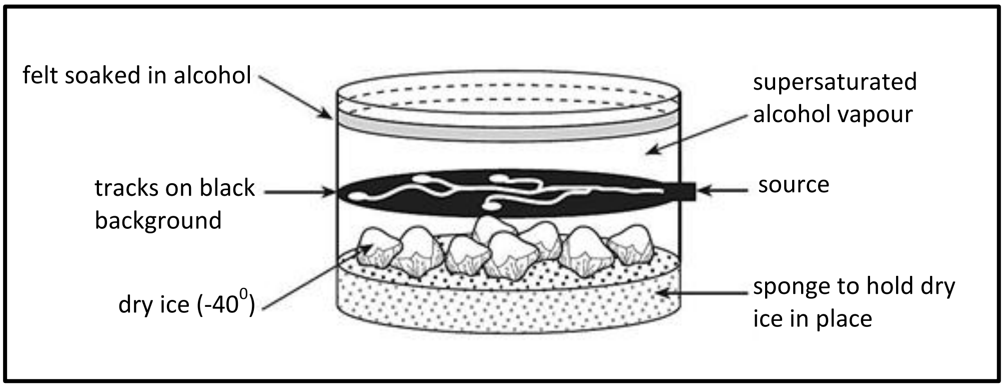


Figure 11 Diffusion cloud chamber

A felt ring inside the top of the chamber is moistened with alcohol. The alcohol vapour diffuses downwards, becoming cooled and ready to condense. Each time a particle is emitted from a radioactive source it produces ions along its path and the alcohol vapour then condenses around these ions. The condensed alcohol droplets reflect light and so can be seen as narrow white lines. The cloud chamber provides evidence that something is being emitted from radioactive materials. It is important to realize that cloud chamber photographs do not show the actual radiation, but only the alcohol droplets which form on the ions produced by such radiation.

The cloud tracks produced by alpha, beta and gamma radiations will look similar to that shown in figure 12.

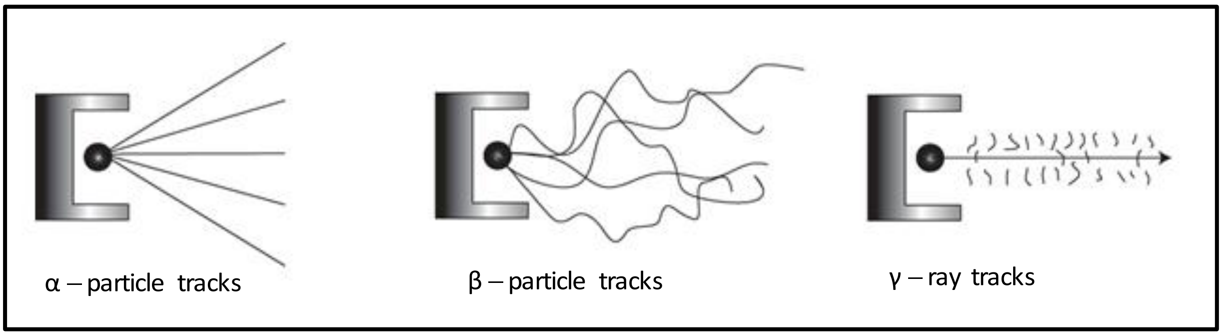


Figure 12 Tracks by alpha, beta and gamma radiations in a diffusion cloud chamber

Now check what you have just learnt by trying out the learning activity on the next page!

Learning Activity 2

40 minutes

Answer the following questions on the spaces provided.

1. Give names and symbols of the three (3) main types of nuclear radiation.

a) ______________________________

b) ______________________________

c) ______________________________

---

2. Which of the three (3) types of radiation described in this section;

a) is the most penetrating? ______________________

b) is the least penetrating? ______________________

c) travels the fastest? ______________________

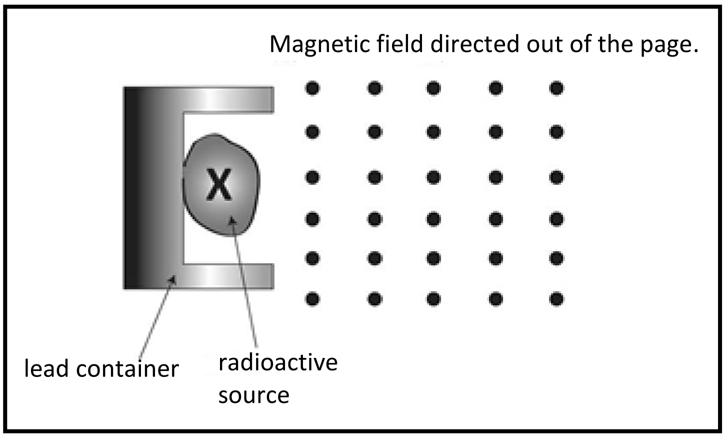
d) is negatively charged? ______________________

e) can penetrate skin? ______________________

f) has the highest ionizing ability? ______________________

---

3. A radioactive substance X is placed in a lead container with a magnetic field that is directed out of the page as shown in the figure below.



What would be the direction of the emitted radiation if **X** produced:

a) alpha radiation? ______________________

b) beta radiation? ______________________

c) gamma radiation? ______________________

4. What property of radiation is harmful to living organisms?

____

5. Which properties of radiation are utilized in the following radiation detectors?

a) Scintillation counter ___________________________________

b) Spark counter ___________________________________

c) Geiger Muller tube ___________________________________

d) Diffusion cloud chamber ___________________________________

Thank you for completing learning activity 2. Now check your work. Answers are at the end of the module.

12.5.2 Radioactivity

Radioactivity is the spontaneous emission of energy in the form of particles or waves (electromagnetic radiation), or both, from the unstable atomic nucleus of certain elements.

The discovery of radioactivity occurred in 1896 when Antoine Henri Becquerel observed that uranium emitted penetrating rays continuously and without initiation. The term radioactivity was coined by Pierre and Marie Curie to designate the process of emitting radioactive rays. They proved that the radioactivity of uranium was an atomic property and not a chemical one. Marie Curie later discovered the radioactive elements polonium and radium in uranium ore. These elements possess shorter **half-lives**, the time it takes for the radioactive decay of one-half of a radioactive sample and are more highly radioactive than uranium.

Ernest Rutherford showed that one of the components of this radiation was deflected upon passage through a thin sheet of metal. He concluded that this phenomenon was due to positive electric charge repulsion between the metal ions of the lattice and a positively charged particle emitted by the radioactive sample and later shown to be a helium ion (an alpha particle). This led to the postulation of the nucleus and was one of the foundations for the formulation of the structure of the atom.

It has been since found that all naturally occurring elements with atomic numbers above 83 are radioactive. A few of the elements with atomic numbers below 83 are also radioactive. Many artificial radioactive nuclides have been produced and put to use in different ways.

It is believed that radioactivity occurs because the atoms in radioactive elements that are unstable break down or decay to become stable and in the process emit radiation in the form of particles and rays. The radiation emitted by a radioactive material is often referred to as nuclear radiation because it comes from the nuclei of the atoms in the material.

Radioactivity

Nature of radioactivity

All radioactive nuclides have definite features in common:

1. They cause certain compounds to shine in the dark (fluorescence). Radiations from radioactive elements produce bright flashes of light when they strike certain compounds. For example, radium causes zinc sulfide to glow in the dark. For this reason a mixture of radium and zinc sulfide is used to make luminous paint.
2. They cause ionization of air molecules. The radiations from radioactive elements knock out or produce an electron from or to molecules of air. This leaves the gas molecules with a positive charge or a negative charge. An atom or group of atoms with charge is called an ion. The production of ions is called **ionization**.
3. They affect a photographic plate. Radiation from radioactive elements can penetrate the heavy black wrapping around a photographic film. When the film is developed it appears black where the radiation struck the film.
4. They undergo a process of decay. The atoms of radioactive elements are continually decaying (breaking down) into simpler atoms as a result of emitting radiation. However, it is not possible to predict exactly when a particular atom will decay.

Nuclear reactions

When the original unstable **parent nucleus** decays, it produces a **daughter nucleus** and at least one other particle. A natural change in the composition of an unstable nucleus leading to changes in atomic number, mass number and the subsequent emission of radiation is called **natural radioactivity** or **radioactive decay**.

Types of radioactive decay

There are four (4) main ways that nuclei decay naturally. They are **alpha (α) decay**, **beta (β^-) decay**, **positron (β^+) decay** and **gamma (γ) decay**.

These four (4) types of decay are associated with three unstable states of a nucleus.

1. If there are too many neutrons, a nucleus will undergo β^- beta decay by emitting an electron ($_{-1}^{0}e$) and energy.
2. If there are too many protons, a nucleus will undergo positive β^+ beta decay by emitting a positron ($_{+1}^{0}e$) and energy.
3. If the nucleus contains too many protons and neutrons (i.e. it has too much mass), it will undergo result in alpha decay by emitting an alpha particle ($_{+2}^{4}He$) and energy.
4. If the nucleus contains excess energy, some of this energy is given off as gamma radiation.

Radioactive decay can be expressed like chemical equations.

Alpha (α) decay

In an alpha decay, the atomic number Z of the nucleus decreases by two and the mass number by four. When an alpha particle is emitted, the atomic mass and atomic number of parent nuclei (${}^{A}_{Z}\mathrm{X}$) decrease by 4 and 2 respectively as shown below.

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{+2}\mathrm{He} $$

When americium-241 $\left({}^{241}_{95}\mathrm{Am}\right)$ emits an alpha particle, it is changed into neptunium-237 $\left({}^{237}_{93}\mathrm{Np}\right)$. This alpha decay is shown by the following nuclear reaction equation:

$$ {}^{241}_{95}\mathrm{Am} \rightarrow {}^{237}_{95}\mathrm{Np} + {}^{4}_{+2}\mathrm{He}\,(\alpha) $$

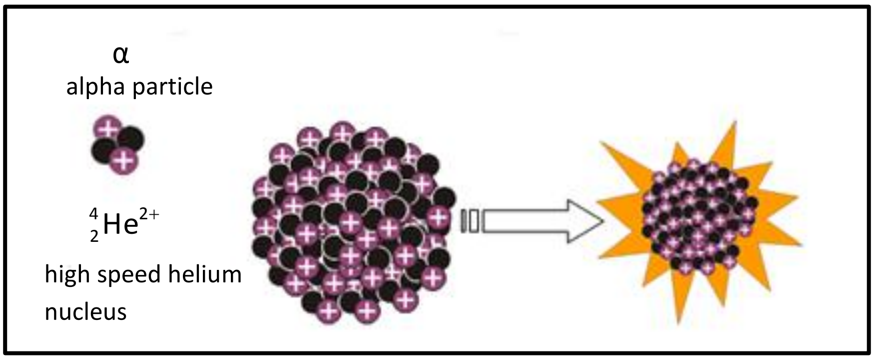


Figure 13 The nucleus' mass number goes down by four while the atomic number goes down by two.

For example, radioactive uranium-238 undergoes alpha decay to produce thorium-234. The daughter nucleus has 2 protons less than the parent nucleus and so it is a different element.

$$ {}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + \alpha $$

$$ {}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{+2}\mathrm{He} $$

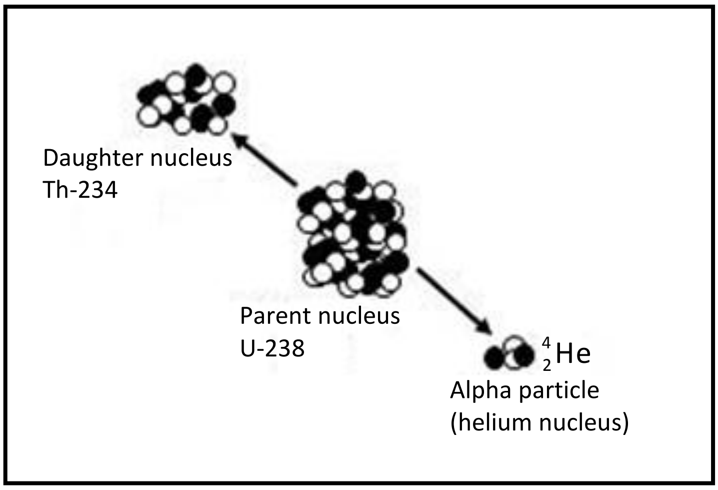


Figure 14 A Uranium-238 nucleus undergoing alpha decay.

Beta (β^-) decay

Beta radiation is due to particles being emitted from the nucleus of radioactive atoms. When a radioactive nucleus undergoes beta **decay** a neutron changes into a proton. During this process, it releases a high-energy electron. The electron is ejected from the nucleus with such a high velocity that it totally escapes the atom.

In beta decay, a neutron in the nucleus changes into a proton and an electron. Since electrons cannot exist in the nucleus for a long period of time, the electron produced is ejected. This results in a nuclear transmutation.

When an electron is ejected from the nucleus, the atomic number **Z** is increased by one but the mass number **A** remains unchanged.

Strontium-90 is a good laboratory source of beta radiation. When strontium-90 undergoes beta decay, the daughter nucleus becomes yttrium-90.

$$^{90}_{38}\mathrm{Sr} \rightarrow {}^{90}_{39}\mathrm{Y} + {}^{0}_{-1}e$$

or

$$^{90}_{38}\mathrm{Sr} \rightarrow {}^{90}_{39}\mathrm{Y} + {}^{0}_{-1}\beta$$

Beta (β^+) decay

Some nuclei of radioactive elements are unstable because they have too many protons in the nucleus, relative to the number of neutrons. These become more stable by a form of beta decay called **positron decay**.

A positron, represented as e^+ or β^+ or sometimes ${}^{0}_{+1}e$ is the **anti-particle** of the electron. It has the same mass as an electron and the same magnitude charge as the electron, but it is positively charged. In positron decay, a proton in the nucleus decays to a neutron and a positron. The atomic number of the decaying nucleus decreases by one but the mass number remains the same. The positron is ejected with high kinetic energy from the nucleus. The most important positron-emitting isotope is fluorine-18, an artificially produced isotope. Its decay equation is:

$$^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + {}^{0}_{+1}e$$

Gamma (γ) emission

When a nucleus emits a gamma ray, the nucleus retains the same atomic number **Z** and mass number **A**. The gamma ray only carries away energy. After removal of some energy, the nucleus becomes more stable.

Gamma decay does not result in the change of atomic number or mass.

Energy and nuclear radiation

Gamma (γ) radiation is given out during alpha and beta decay. It is the energy due to the mass lost during the nuclear reaction and usually given off as photons or electromagnetic waves. All radioactive decay reactions can be written showing the energy release as shown in the alpha decay of Plutonium-234 below.

$$^{234}_{94}\mathbf{Pu} \rightarrow {}^{4}_{2}\mathbf{He} + {}^{230}_{92}\mathbf{U} + \gamma \text{ , where, } \gamma \text{ is the energy released.}$$

We can write the equation as, $^{234}_{94}\mathbf{Pu} \rightarrow {}^{4}_{2}\mathbf{He} + {}^{230}_{92}\mathbf{U} + \mathbf{energy}$. In most cases however, we exclude energy but that does not mean that it is not present.

An unstable nucleus releases energy by emitting radiation during radioactive decay. The amount of energy released is given by Albert Einstein's famous equation.

$$E = mc^2$$

The equation implies that matter is a form of energy. **E** refers to energy, **m** is mass and **c** is the speed of light (3×10^8m/s). A small amount of an atom's matter (mass) is converted to an equivalent amount of energy during radioactive decay. If an atom's nucleus has the right balance of protons and neutrons, it can stay stable and can last forever.

Balancing nuclear reactions

Below is an example of a nuclear reaction to describe the decay of Uranium-238.

$$^{238}_{92}\mathbf{U} \rightarrow {}^{234}_{90}\mathbf{Th} + {}^{4}_{+2}\mathbf{He}$$

Here a parent nucleus the uranium (^{238}U), splits into a daughter nucleus (^{234}Th) and an alpha particle(s) is radiated.

In a nuclear reaction, both mass number and charge are conserved. Balancing a nuclear reaction requires that we must ensure that the sum of atomic masses and the sum of nuclear charges are equal on both sides of the equation.

Below are some rules that you must follow when balancing nuclear reactions.

1. **The sum of the atomic masses on the left of the equation must be the same as the sum of the atomic masses on the right.**
   In the above case the mass is 234 + 4 = 238, so this rule is satisfied.
2. **The total charge on the left-hand side of the equation must equal the total charge on the right-hand side.**
   Charge refers to the nuclear charge and that of its emitted particles.
   - A proton has a charge of +1
   - An electron (β^- particle) has a charge of –1

- A positron (β^+ particle) has a charge of +1.
  In the case above, the left-hand side shows 92 protons, so the charge is +92 or simply 92. The sum of the nuclear charges on the right is 90 + 2 = 92; so the rule is obeyed.

3. **The number of protons (atomic number) determines the name and symbol of the element.**
   A common mistake that students make when trying to work out the symbol for the daughter element is to use the **atomic mass** rather than the **atomic number**.

   Below are several examples of balancing nuclear equations.

   Example 3
   Balance the following radioactive plutonium-234 decay, radiating an alpha($\propto$) particle and name the daughter element formed.

$$^{234}_{94}\text{Pu} \rightarrow {}^{4}_{2}\text{He} + ?$$

Solution:

Step 1. The atomic masses of the right hand side must equal the atomic masses of the left hand side. In this case, it has to be equal to 234 on both sides. Since an alpha-particle is a Helium atom, it has an atomic mass of 4 and atomic number of 2. The daughter nucleus must have an atomic mass of 234 less 4 (234 – 4 = 230), that is A = 230.

Step 2. The nuclear charges or atomic number must be equal to 94, so the daughter nucleus must have a nuclear charge of 94 minus 2 (94 – 2) = 92, that is Z = 92.

Step 3. The nuclear charge or atomic number determines the name of the daughter element from the periodic table; Z = 92 refers to uranium.

Therefore Uranium is the daughter nucleus formed
The complete nuclear reaction is:

$$\mathbf{^{234}_{94}Pu \rightarrow {}^{4}_{+2}He + {}^{230}_{92}U}$$

Let’s look at some more examples involving radioactive decay reactions. You may need to use a periodic table to identify and name some of the following elements.

Example 4

Write a nuclear reaction for the alpha (α) decay of Thorium-230 $\left({}^{230}_{90}\mathrm{Th}\right)$ and name the daughter element formed.

Solution

Alpha decay means the emission of an alpha particle $\left({}^{4}_{+2}\alpha\right)$.

$${}^{230}_{90}\mathrm{Th} \rightarrow {}^{4}_{+2}\alpha + ? + \text{energy}$$

Since an alpha particle is emitted, the mass number of Thorium will decrease by 4 while the atomic number of Thorium will decrease by 2. Therefore, the daughter element formed will have a mass number of 230 – 4 = 226, and an atomic number of 90 – 2 = 88.

$${}^{230}_{90}\mathrm{Th} \rightarrow {}^{4}_{+2}\alpha + {}^{226}_{88}? + \text{energy}$$

Looking at the periodic table, we can see that the element with an atomic number of 88 is Radium (Ra). The final nuclear reaction for the alpha decay of Thorium -230 is;

$${}^{230}_{90}\mathrm{Th} \rightarrow {}^{4}_{+2}\alpha + {}^{226}_{88}\mathrm{Ra} + \text{energy}$$

The daughter element formed is Radium (Ra).

Example 5

Polonium-210 is formed from the beta decay $\left({}^{0}_{-1}\beta\right)$ of an element X. Find the element X and state its atomic number and atomic mass.

Solution

Looking at a periodic table, we see that the atomic number of Polonium (Po) is 84. The nuclear reaction equation is;

$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{210}_{84}\mathrm{Po} + {}^{0}_{-1}\beta + \text{energy}$$

From the equation, observe that the beta particle has 0 mass, therefore, the mass number for element X is 210. The beta particle has an atomic number of -1, therefore the atomic number of X is Z = 84 – 1 = 83.

Looking at the periodic, table we see that the element that has an atomic number of 83 is Bismuth (Bi).

Therefore the element X is Bismuth with an atomic number of 83 and mass number of 210.

$$\left({}^{210}_{83}\mathrm{Bi}\right)$$

Example 6

A radioactive isotope ${}^{A}_{Z}X$ decays by β-emission to a nuclide which decays to another nuclide by α-emission which itself decays by β-emission. Which of the following represents the final nuclide Y?

A. ${}^{A-2}_{Z-2}Y$ B. ${}^{A-2}_{Z}Y$ C. ${}^{A-4}_{Z}Y$

D. ${}^{A-4}_{Z+1}Y$ E. ${}^{A-6}_{Z-2}Y$

Solution

We can also solve this by writing a combined nuclear reaction equation for 1 alpha decay and 2 beta decays.

$$\mathbf{{}^{A}_{Z}X \rightarrow {}^{4}_{2}\alpha + 2\left({}^{0}_{-1}\beta\right) + {}^{A-4}_{Z}Y}$$

Answer: C

Now check what you have just learnt by trying out the learning activity below!

Learning Activity 3

30 minutes

Answer the following questions on the spaces provided.

1. Define the term nuclear transmutation.

____

____

____

____

____

---

2. Briefly describe how the atomic number and atomic mass of an isotope is changed by:

a) alpha (α) decay.

____

____

____

____

b) beta (β^-) decay.

____

____

____

____

c) positron (β^+) decay.

____

____

____

____

d) gamma (γ) emission.

____

____

____

____

---

3. What type of radioactive decay occurs when an unstable nucleus has too many;

a) neutrons? _______________________

b) protons? _______________________

c) protons and neutrons? _______________________

---

4. For the following nuclear reactions, find the numbers represented by each letter.

(a) ${}^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \rightarrow {}^{w}_{14}\text{Si} + {}^{1}_{1}\text{H}$ w = ____________________

(b) ${}^{214}_{83}\text{Bi} \rightarrow {}^{4}_{2}\text{He} + {}^{210}_{81}\text{X}$ X = ____________________

(c) ${}^{27}_{14}\text{Si} \rightarrow {}^{0}_{-1}\text{e} + {}^{y}_{15}\text{P}$ y = ____________________

(d) ${}^{66}_{29}\text{Cu} \rightarrow {}^{66}_{30}\text{Zn} + {}^{L}_{M}\text{e}$ L = ____________________

M = ____________________

---

5. Write decay equations and the name of the daughter elements formed for each of the following radioactive decays.

(a) α-decay of Radium-224

decay equation:

____

daughter element

____

(b) β-decay of Lead-214

decay equation: ____

daughter element: ____

(c) β-decay of Actinium-227

decay equation: ____

daughter element: ____

(d) α-decay of Bismuth-213

decay equation: ____

daughter element: ____

---

6. Radium-228 (^{228}Ra) was the daughter nuclide formed from the alpha decay of a parent nuclide. Determine the atomic number and mass number of the parent nuclide.

---

7. Lead-209 (^{209}Pb) was the daughter nuclide formed from the beta decay of a parent nuclide. Write the symbol of the parent nuclide.

8. A radioactive isotope $^{A}_{Z}\mathbf{X}$ decays by two (2) α-decays followed by a β-decay. Find the mass and atomic numbers of the resulting nucleus Y.

Thank you for completing learning activity 3. Now check your work. Answers are at the end of the module.

Decay series (decay chains)

Sometimes a radioactive isotope decays into another isotope that is also radioactive. The initial unstable nucleus is called the **parent nucleus**. It transforms by emitting particles and energy. The result of the emissions is another nucleus called the **daughter nucleus**. This daughter nucleus, if unstable may also decay into another isotope, which may also decay further, and so on until a stable daughter atom is formed.

A successive chain of decays is called a **decay series**. An example of a decay series is shown in Figure 15 on the next page in which uranium-238 decays by alpha emission to thorium-234, which in turn decays by beta emission shown with a line pointing to the right then further and so on until the stable isotope lead-206 is reached.

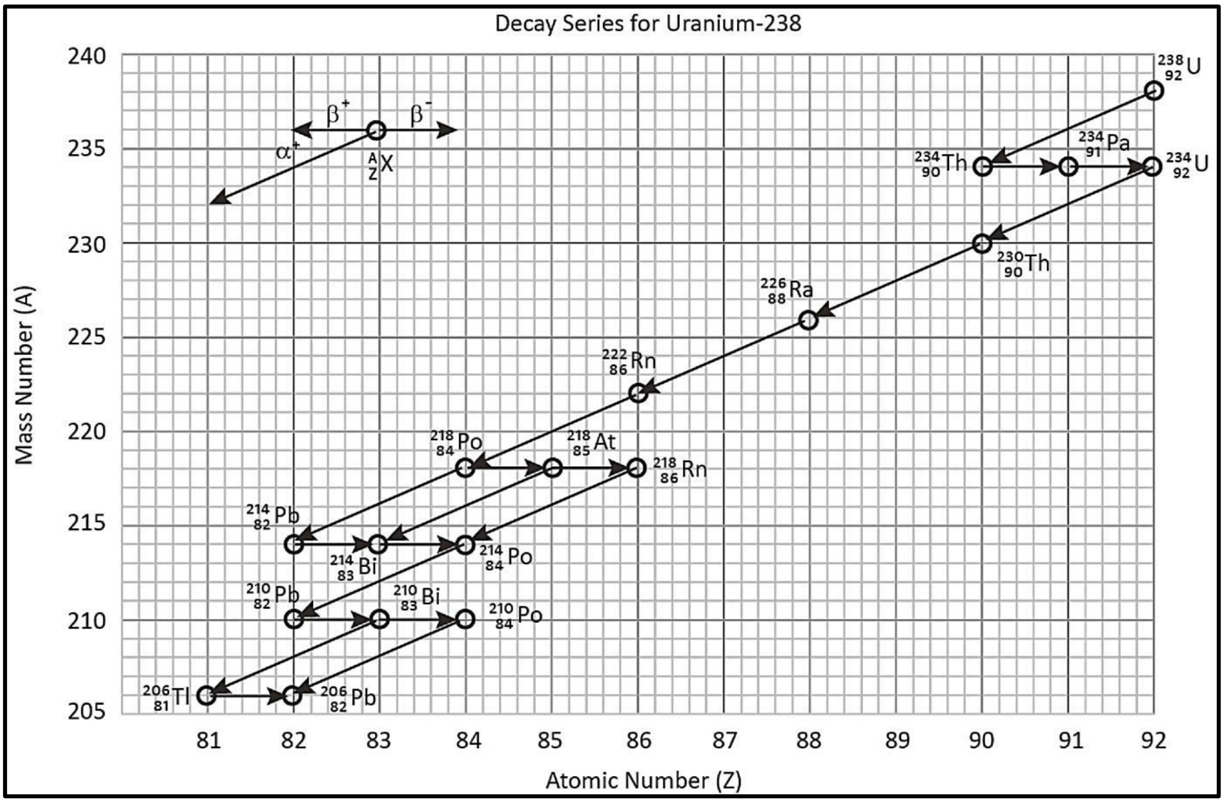


Figure 15 The successive decay series of Uranium-238

Let us look at the chart of uranium-238 shown in Figure 15. The decay series, starts at the top right hand corner with uranium-238 decaying by alpha emission. Since alpha particle is a helium nuclei with 4 atomic mass and 2 atomic number, the daughter nuclei must have an atomic number that is 2 less and a mass number less 4, than the parent nuclei. Thorium-234 satisfies the condition so a diagonal line towards the bottom left is drawn pointing at Th-234.

Thorium-234 goes through a beta decay producing a palladium-234 daughter nucleus. The atomic mass does not change but the atomic number goes up by one, so we see a line is drawn horizontally to the right indicating on the chart no change in atomic mass but an increase in atomic number. Then palladium-234 undergoes a beta decay producing uranium-234 with atomic number 92, shown on the chart with a horizontal line to the right indicating no change in atomic mass but an increase in atomic number. Uranium-234, then goes through alpha decay, losing 4 atomic mass units and also losing 2 atomic number units as shown by a diagonal line to the bottom left of its position.

In order to understand and be able to read a decay series charts, we must take note that a directed horizontal line to the right indicate negative beta decay and the opposite indicates positron decay. A diagonal line represents an alpha decay.

In an alpha decay, the equivalent of a helium atom is lost so the atomic mass decreases by 4 and the atomic number decreases by 2. This appears as a diagonal arrow. Beta emission and positron emission have no effect on atomic mass therefore they appear as arrows to the right and left respectively.

Now check what you have just learnt by trying out the learning activity below!

Learning Activity 4

50 minutes

Answer the following questions on the spaces provided.

Study the decay series chart shown in figure 15 and answer the following questions.

1. What is a decay series?

   ____

2. At Polonium-218 ($^{218}_{84}\text{Po}$), there are two arrows (one diagonal and one to the right). Why do you think there are two (2) arrows drawn from $^{218}_{84}\text{Po}$?

   ____

   ____

3. What type of radioactive decay is represented on a decay series by a/an:

   a) diagonal arrow to the bottom left? ________________________

   b) arrow to the left? ________________________

   c) arrow to the right? ________________________

4. How many times does a nuclide of Polonium occur in the decay series?

   ____

5. List the nuclides of lead that occur in this decay series.

   ____

   ____

6. List the elements that have nuclides which appear twice or more times in the decay series.

   ____

   ____

Thank you for completing learning activity 4. Now check your work. Answers are at the end of the module.

Units of radioactivity

Radioactivity is measured as a **rate of decay**. That is, by counting the number of nuclei which disintegrate over a period of time. The term disintegrate, refers to the emission of radiation since the occurrence of radiation means that one or more nuclei have transmutated.

The SI unit for the rate of radioactive decay (**activity**) is **Becquerel** (**Bq**), so **1 Bq = 1 disintegration per second** (**1 dps**). In less active substances or atoms, the activity may be expressed as **disintegrations per minute (dpm)**, where **1 dpm =** $\frac{1}{60}$ **dps =** $\frac{1}{60}$ **Bq**.

The standard unit of radioactivity is the **curie (Ci)**, which is defined as the number of disintegrations occurring in one gram of radium per second. Radium was chosen because it was available in pure form and it has a long half-life of 1,600 years.

The curie is equivalent to 3.7 X 10^{10} disintegrations per second (dps) or Bq. The curie is a large unit, so several fractions of this unit have found wide use. The **milli-curie (mCi) is equal to one-thousandth of a curie or 3.7 X 10^7 dps**, while the **micro curie (µCi) is equal to one-millionth of a curie, or 3.7 X 10^4 dps, or 2.22 X 10^6 disintegrations per minute (dpm)**.

Half-life

Radioactive decay is a random event, just as a car accident is a statistically random event. There is no means of predicting whether a particular driver will be involved in a crash. However, it is possible to say statistically how many crashes will happen in Papua New Guinea each year. The more cars there are, the more accidents there are. In a similar way, it is quite impossible to predict when a particular nucleus will decay but it is possible to predict the number of nuclei that will decay in a given time from a particular source.

Method of half-lives

The **half-life** of a radioactive isotope is the time taken for half the radioactive atoms in a sample to decay.

If N_0 = the number of parent nuclei at the start and N = the number of atoms at end of the time period n, the number of half-life:

After one half-life: $\mathbf{N = N_0 \times \frac{1}{2}}$

After n half-lives: $\mathbf{N = N_0 \times \left(\frac{1}{2}\right)^n}$

Example 7

Iodine-131 has a half-life of eight (8) days and undergoes beta decay with the nuclear reaction of:

$$^{131}_{53}\text{I} \rightarrow {}^{131}_{54}\text{Xe} + {}^{0}_{-1}\text{e}$$

If a milk sample contains 3 × 10^{18} atoms of Iodine-131, at a particular time, calculate:

a) The number of iodine atoms remaining after 60 days.

b) The time that would take for 1 million iodine atoms to remain in the milk sample.

Solution

a) Number of half-lives (n) in 60 days is 60 days divided by 8days:

$$\text{Half-life, } n = \frac{60}{8} = 7.5 \text{ half-lives}$$

$$\text{Therefore, } N = N_0 \times \left(\frac{1}{2}\right)^n \text{ the number of atoms remaining}$$

$$N = 3 \times 10^{18} \times \left(\frac{1}{2}\right)^{7.5} = 1.6 \times 10^{16} \text{ atoms remaining.}$$

b) In order to determine the time it would take for 1 million iodine atoms to remain in the milk sample, we first need to find out how many half-lives (n) would occur before this happens.

$$N = N_0 \times \left(\frac{1}{2}\right)^n$$

$$1 \times 10^6 = 3 \times 10^{18} \times \left(\frac{1}{2}\right)^n$$

$$\frac{1 \times 10^6}{3 \times 10^{18}} = \left(\frac{1}{2}\right)^n$$

$$3.333 \times 10^{-13} = \left(\frac{1}{2}\right)^n$$

$$\log 3.333 \times 10^{-13} = \log\left(\frac{1}{2}\right)^n$$

$$\log 3.333 \times 10^{-13} = n \log\left(\frac{1}{2}\right)$$

$$-12.48 = -0.301 \times n$$

$$\text{Therefore, } n = \frac{-12.48}{-0.301} = 41.46$$

If the one half-life is 8 days, then the time for one million atoms to remain is:

$$41.46 \times 8 = 332 \text{ days}$$

Example 8

Nitrogen-13 decays to Carbon-12 by positron emission:

$$^{13}_{7}\text{N} \rightarrow {}^{12}_{6}\text{C} + {}^{0}_{+1}\text{e}$$

Solution

If we had 10,000 Nitrogen-13 atoms, about 12 of them would decay in 1 second (12 s^{-1}). We say the **decay rate** or **activity** (**a**) is 12 disintegrations per second (dps) or **a** = 12 s^{-1}. So after 1 second there would be 9988 left. After another second about 12 more nitrogen-13 atoms would decay and there would be 9976 left.

As the number of nitrogen-13 atoms decreases so too does the decay rate. After 10 minutes, there would be about 5000 nitrogen-13 atoms left, that is half the starting number and the decay rate would be 6 disintegrations per second. When another 10 minutes had elapsed, there would be about 2500 atoms of nitrogen-13 left and the decay rate would be down to 3 dps.

The period of 10 minutes in which it takes half the nitrogen-13 atoms to decay is called the **half-life** (**$t_{1/2}$**). It also represents the time taken for the decay rate to fall to half its original rate.

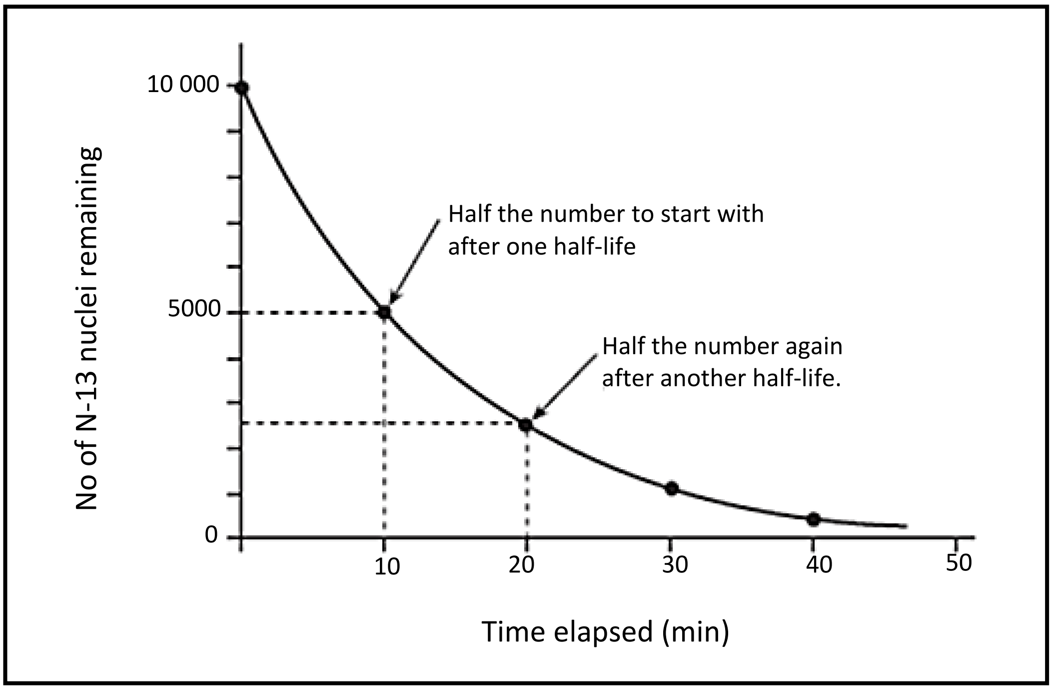


Figure 16 Graph of nitrogen-13 decay

After one half-life, only 50% of the original parent isotope remains; 50% of that remaining amount decays after another half-life, leaving just 25% of the original parent isotope and so on.

The half-life of a radioactive isotope can be deduced from a graph showing the mass of the remaining radioactive atoms of the element plotted against time. In figure 17, the time taken for 2000g of strontium-90 to be reduced to 1000g is 28.1 years, the half-life of strontium-90. The daughter isotope is yttrium-90, which rapidly decays to zirconium-90, which is stable.

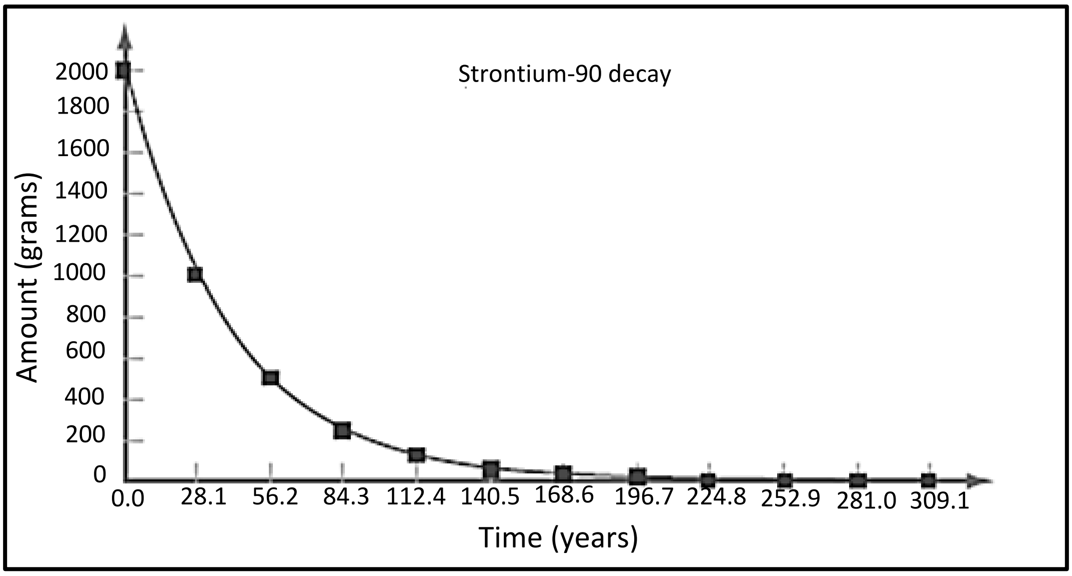


Figure 17 Graph of Strontium-90 decay

The mathematical model shown above in figure 17 is called **exponential decay**. It is applicable to all forms of radioactive decay. The rate of radioactive decay of an isotope is not affected by changes in physical conditions such as temperature or pressure.

The decay rate is unchanged by any chemical reactions or compounds in which the radioactive isotope may be incorporated. Every radioisotope has its own half-life.

Now check what you have just learnt by trying out the learning activity below!

Learning Activity 5

50 minutes

Answer the following questions on the spaces provided.

1. Define the following terms.

a) Radioactivity

____

____

____

____

b) Becquerel

____

____

____

____

____

c) Curie

____
____
____
____
____

d) Half-life

____
____
____
____
____

---

2. Half-lives can be very short and can be very long. Do some research and find the half-life and the type of decay of the following isotopes.

a) Bismuth-210 ____
b) Uranium-234 ____
c) Thorium-234 ____
d) Radon-222 ____
e) Polonium-218 ____
f) Polonium-214 ____
g) Carbon-14 ____

---

3. A radioisotope has a half-life of 4 days. How much of a 20 gram sample of this radioisotope will remain at the end of each time period of:

a) 4 days? ______________________________
b) 8 days? ______________________________
c) 16 days? ______________________________

Thank you for completing learning activity 5. Now check your work. Answers are at the end of the module.

Exponential decay

The most common method for studying radioactive nuclides is by using a mathematical model called **exponential decay**.

This model gives a general equation which is used to estimate the number of nuclei (N) remaining after some time (t).

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

Where N = the number of nuclei remaining at time t, N_0 = (original) number of nuclei at t = 0, e = Euler's number or the natural base = 2.71828, λ = decay constant, t = time in seconds.

The **decay constant** (λ) is a constant of proportionality that directly relates the activity of a sample to the number of radioactive nuclei present in a sample. We can calculate the decay constant using the equation;

$$\lambda = \frac{\text{activity of sample}}{\text{number of radioactive nuclei in the sample}}$$

One important point to note is that the decay constant is a unique value for each radioactive nuclide. From this equation, we can also note that the activity of a sample depends on the number of radioactive nuclei in the sample. That is, if the number of nuclei in a sample decreases, the activity should also decrease so that the decay constant is maintained.

In the exponential model, the half-life of a radioactive nuclide depends on the decay constant. This relationship is given by the following equation.

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

Where $T_{1/2}$ = half-life of a radioactive isotope in seconds, ln 2 = 0.693 which is a constant number (read as " the natural logarithm to base e of 2") and λ = decay constant.

From the exponential decay model, the amount of time (t) it takes for a certain portion of the original nuclei to remain in sample.

$$t = \frac{\ln(N_0) - \ln(N)}{\lambda}$$

Let's look at some examples of using exponential decay.

Example 9

Phosphorus-30 is a radioactive substance with a half-life of 2.50 minutes. A 6.0g sample of this radioisotope is studied. How much of this isotope will remain after 3.0 minutes?

Solution

First let's determine the decay constant λ.

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

$$\lambda = \frac{0.693}{2.50\,\text{min}}$$

$$\lambda = 0.2772\,\text{min}^{-1}$$

Note that the decay constant is given in the unit min^{-1} (per minute).

Now we can find N.

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

$$N = 6 \times e^{-0.2772 \times 3}$$

$$N = 2.61\,\text{g}$$

Example 10

Actinium-228 has a half-life of 6.15 hours. For an initial sample of 4 grams of Actinium-228, determine the:

a) decay constant.

b) number of nuclei present at t = 1 hour.

Solution

a) 6.15 hrs = 6.15 × 3600s = 22 140 seconds

Using the half-life equation, we can find λ.

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

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

$$\lambda = \frac{\ln 2}{22\,140\text{s}}$$

$$\lambda = 3.13 \times 10^{-5}\,\text{s}^{-1}$$

1 hour = 3 600 seconds

Avogadro's number = 6.02×10^{23} atoms/mole

Mass of 1 mole of Actinium-228 = 228g

The number of atoms in 4g of Actinium-228 is calculated as follows.

$$N_0 = \frac{4}{228} \times 6.02 \times 10^{23}$$
$$N_0 = 1.056 \times 10^{22} \text{ atoms}$$

At t = 3600 seconds, the number of nuclei present is calculated as follows.

$$N = N_0 e^{-\lambda t}$$
$$N = 1.056 \times 10^{22} \times (2.782)^{[-(3.13\times10^{-5}) \times 22140]}$$
$$N = 5.28 \times 10^{21} \text{ nuclei}$$

Example 11

A radioactive source contains 1.0 × 10^{-6} grams of Plutonium-239. It is estimated that this source emits 2300 α-particles per second with the formation of Uranium-235.

a) Write a nuclear reaction for the α-decay of Plutonium-239.

b) Find the number of atoms in 1.0 × 10^{-6} grams of Plutonium.

c) Calculate the decay constant λ for Plutonium-239.

d) Calculate the half-life of Plutonium-239 in seconds.

Solution

a) The decay equation for the α-decay of Plutonium-239 is

$$^{239}_{94}\text{Pu} \rightarrow {}^{235}_{92}\text{U} + {}^{4}_{+2}\text{He}$$

b) Given that Avogadro's number = 6.02 × 10^{23} atoms/mole
Mass of 1 mole of Plutonium-239 = 239g

The number of atoms in 1.0 × 10^{-6}g of Plutonium is calculated as follows.

$$N = \frac{1.0 \times 10^{-6}}{239} \times 6.02 \times 10^{23}$$
$$N = 2.52 \times 10^{15} \text{ atoms}$$

c) The decay constant is calculated as shown below.

$$\lambda = \frac{\text{activity}}{\text{numberof atomsinoriginalsample}}$$
$$\lambda = \frac{2\,300 \text{ s}^{-1}}{2.52 \times 10^{15} \text{ atoms}}$$
$$\lambda = 9.13 \times 10^{-13} \text{ s}^{-1}$$

d) The half-life of Plutonium-239 is calculated as shown below.

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

$$T_{1/2} = \frac{\ln 2}{9.13 \times 10^{-13}}$$

$$T_{1/2} = 7.59 \times 10^{11} \text{ seconds}$$

Example 12

Carbon -14 is a radioactive isotope present in life forms. It is used to determine the age of organic remains from plants, animals and humans. Carbon-14 has a half-life of 5370 years. The remains of a prehistoric animal were found to contain 0.178g of carbon-14. The animal was thought to have 2kg of carbon-14 when it died. Calculate the approximate age of the animal's remains.

Solution

First we must determine the decay constant for carbon-14 per year.

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

$$\lambda = \frac{\ln 2}{5\,730\,\text{yr}}$$

$$\lambda = 1.2097 \times 10^{-4}\ \text{yr}^{-1}$$

Now that we know the decay constant, we can work out the age of the animal since we are given the following information.

$N = 0.178\text{g}$, $N_0 = 2\text{kg}$, $\lambda = 1.2097 \times 10^{-4}\ \text{yr}^{-1}$, we use the following equation,

$$t = \frac{\ln(N_0) - \ln(N)}{\lambda}$$

$$t = \frac{\ln(2) - \ln(0.178)}{1.2097 \times 10^{-4}}$$

$$t = 19,\ 997$$

Therefore the age of the animal's remains is approximately 20, 000 years.

Now check what you have just learnt by trying out the learning activity on the next page!

Learning Activity 6

50 minutes

Answer the following questions on the spaces provided.

1. What is the decay constant?

____

____

____

2. Nitrogen-13 has a decay constant of $1.16 \times 10^{-3} s^{-1}$. For an initial amount of 60g, determine the:

   a) half-life of Nitrogen-13 in minutes.

   ____

   b) the mass of Nitrogen-13 after 20 minutes.

   ____

   c) the number of Nitrogen-13 atoms after 20 minutes.

   ____

3. 12g of radioactive Chromium-48 is left in a room. 12 hours later the amount of chromium remaining is found to be 8.17g. Determine the:

   a) decay constant in disintegrations per hour (hr^{-1}).

   ____

   b) half-life of Chromium-48 in hours.

   ____

4. Caesium-124 ($^{124}_{55}Cs$) has a half-life of 31 s.

   a) Calculate its decay constant in s^{-1} and min^{-1}.

b) If there was 20.0g of Cs-124 to start with, state how much will be left (in grams) after;

(i) 62s

(ii) 124s

(iii) 10 minutes

Thank you for completing learning activity 6. Now check your work. Answers are at the end of the module.

Uses of Radioisotopes

There are many applications for radioisotopes in industry, energy production and medicine.

Uses in agriculture and food preservation

Radioisotopes are used in agricultural research as **tracers**. A small amount of a radioisotope is mixed with fertilizers and then added to the soil. When plants take their nutrients from the soil, the amount of nutrients can be measured by detecting the amount of radiation absorbed by the plant.

Gamma radiation can be used to increase the shelf-life of foods by slowing the process of ripening and stopping the sprouting of vegetables like potatoes and onions. Although the food does not become radioactive, irradiation can cause physical and chemical changes in the food. When molecules are split by nuclear radiation, the fragments are called **radiolytic** products. Although 50 years of research has shown irradiation to be useful and generally safe, there is concern that these radiolytic substances could be carcinogenic (cancer-forming).

To date, in Australia and New Zealand, only herbs and spices and some tropical fruits have been approved to be irradiated for sanitary reasons and to a strict maximum amount of radiation. The tropical fruits include breadfruit, carambola (star fruit), custard apple, mango, papaya (pawpaw) and rambutan. Food that has been irradiated must be labeled with a statement that says it has been treated with ionising radiation.

Mechanical wear analysis and detection of leakages

Gamma rays can be used to examine the interior of solid objects such as the welds in natural gas pipelines.

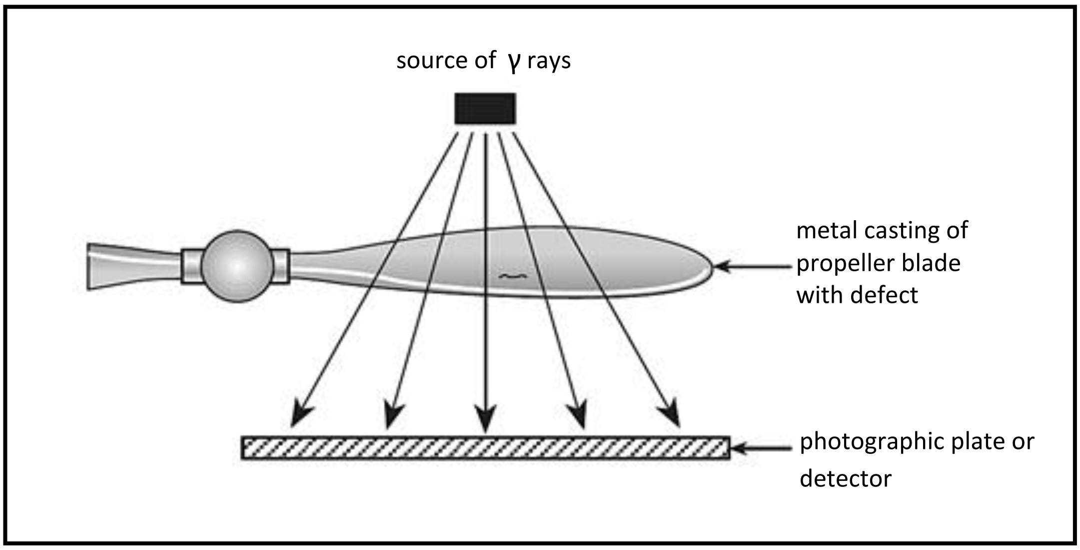


Figure 18 Examining a propellor blade with a crack (defect).

To check how engine parts are worn down by different lubricating oils, a small amount of radioactive tracer is added to the metal used to make the parts. When the lubricating oil is used, the parts wear off and small amounts of metal fall into the lubricating oil. The radioactivity of the lubricating oil can be measured and the test can be repeated for various types of lubricating oil. In this way engineers can determine which oil causes the least wear and allows for the engine to last longer.

Leakages in underground pipes can be detected by using a tracer as well. A small amount of a radioisotope, is mixed with the fluid in a pipe. Any leakage can be detected by using a detector such as a G-M tube above the ground.

Slow moving particles such as neutrons can be used as a type of X-ray to obtain a clear image of the internal structure of metals and other objects. Some atoms are strong absorbers of slow neutrons and when they absorb the neutrons, clear images can be obtained by using suitable detectors. Some common uses in creating images from radioactive particles are to detect flaws in gas turbine blades, corrosion of aircraft components and the presence of explosives in luggage.

Thickness gauging

Radiation intensity is reduced when matter is placed between a source and a detector. The thickness of a sheet of metal can be monitored by measuring the intensity of radiation through it. Rollers used to produce metal sheets can be automatically adjusted to maintain a thickness of incredible uniformity. This is illustrated in figure 19.

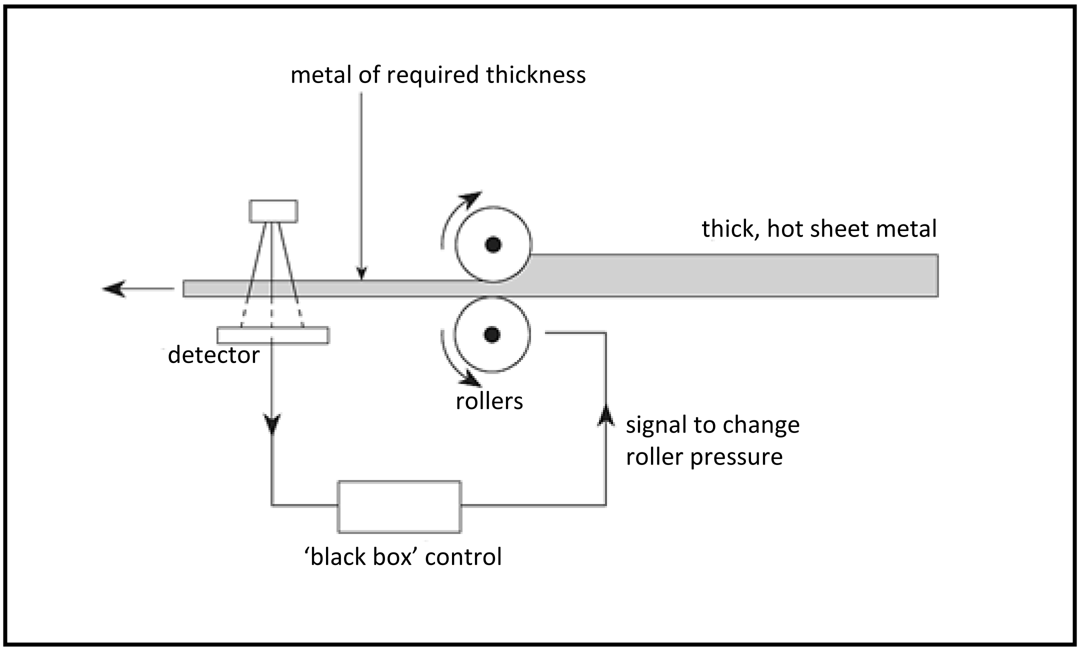


Figure 19 Monitoring the thickness of a sheet of metal in a factory**.**

The thickness of paper, steel and glass are some areas where radioactive gauging is also used.

Radioactive dating

Some radioisotopes have very long half-lives. This property is often used to determine the age of substances in research fields such as archaeology and geology.

Radiocarbon dating is a technique used in archaeology and history. It makes use of Carbon-14 ($^{14}_{6}C$) which is a radioactive isotope of carbon with a half-life of approximately 5 700 years. It is formed in the atmosphere by the action of cosmic rays on Nitrogen-17. This reaction is shown below.

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

This isotope of carbon is present in carbon-dioxide and is absorbed by plants (through photosynthesis) and animals (through feeding). When an animal or plant dies, they stop absorbing carbon-14. The amount of carbon-14 that is present when a living thing dies remains and naturally decays.

By measuring the amount of carbon-14 in animal or plant remains, we can determine how old the remains of a plant or animal are. Many useful discoveries in archaeology, paleontology and history have been made using this technique.

Other radioactive isotopes have very long half-lives. One such example is Uranium-238. It has a half-life of about 4.5 billion years. Uranium-238 has a decay series that ultimately ends when the stable isotope lead-206 is formed. In geology, the age of rocks that contain isotopes such as Uranium-238 and lead-206 can be determined by working out the ratio of both isotopes. This is one technique that allowed us to determine when the Earth was formed.

Uses in medicine

Radioisotopes are widely used in medicine. Some of the main medical uses of radioisotopes are in sterilizing, tracing, medical imaging and medical treatment.

Gamma radiation is often used to make surgical instruments sterile. At any given time, microbes can be found on all objects. In surgical operations, the instruments used must be properly treated so as to minimize any infection to patients. The gamma radiation applied to surgical instruments kills any microbes that are found on instruments used during surgery. This radiation is not absorbed by the instruments.

Some specialized artificial radioisotopes are used as tracers because of their ability to attach to chemical compounds in the body. Such radioisotopes are used to make special compounds called **radiopharmaceutical** compounds. One such radioisotope is technetuim-99m (^{99m}Tc). The most common features of radioisotopes used as tracers in medicine are;

1. Have a short half-life, usually a few hours.
2. Decay by gamma rays and low energy electrons, which do not cause a lot of ionization.
3. They can form compounds that can attach to certain biochemicals used in different organs of the body.

Tracers used in medicine can help doctors diagnose diseases of the organs such as the heart, lungs, kidneys and liver.

Radioisotopes also assist medical professionals to take pictures of the body in medical imaging. The isotopes that produce gamma radiation are particularly useful because gamma radiation is highly penetrative and has low ionisation ability. As technology develops, newer methods are being developed that are safer and more effective.

Radiation therapy refers to any treatment technique that is used to deliver a lethal radiation dose to a specific organ or site in the body while minimizing the dose to surrounding tissues. The most common method radiation therapy use is internal radioisotopes as tracers that target specific sites or external rotation techniques that allow concentration of radiation beams to very specific sites. Examples of isotopes used for these therapeutic purposes are cobalt-60 and caesium-137. Therapeutic radioisotopes are most commonly used in the treatment of cancerous tumours. In treating cancer, radiation doses are applied to specific targets which are aided by using radioactive tracers that chemically bind to the DNA of the cancer cells. This method helps to make sure that radiation to other healthy tissue is minimized.

Energy production, scientific research and nuclear weapons

Nuclear reactors are special devices that allow for the energy and products that are produced during nuclear reactions to be used for generating power and for other uses.

Many industrial nations have developed nuclear reactors to produce electricity. The main by-product of a nuclear reaction is heat. This is used to produce steam which turns turbines that generate electricity. Although this appears to be a better alternative to fossil fuels, there is still the problem of disposing the radioactive waste products from nuclear reactions. There is also the potential for widespread pollution from accidents that can occur such as at Chernobyl in 1986 and more recently at Fukushima in 2011.

Apart from harnessing the energy in a nuclear reaction, the products of nuclear reactions can also be used. Many of the radioisotopes that are used in other fields are “manufactured” or purposely made in nuclear reactors. This includes the radioisotopes used for industries and medicine. A few hospitals in the world have small nuclear reactors on site that help produce radioisotopes for medical uses.

Scientific research also requires the use of nuclear reactors and particle accelerators. Recently, three (3) new elements were added onto the periodic table. These elements where produced using techniques which resulted in the change to heavy nuclei. More research is also being done to determine further uses for other radioisotopes that are produced in nuclear reactions.

Another use of radioisotopes is in the production of nuclear weapons. The most common isotope used is Uranium-238 which naturally occurs. Rocks containing this isotope are mined and then taken to nuclear reactors where they are **enriched** by converting some of the uranium-238 atoms into uranium-235 which is the most common isotope used in nuclear weapons. This can also be used to produce radioactive plutonium which is an even better isotope for use in nuclear weapons.

Some countries that have developed nuclear weapons use them as a **deterrent**. This means that they keep the weapons to show how powerful they are and make sure that their enemies do not provoke them. A country that possesses a nuclear weapon is often treated as a military threat. This was the case with Iran which almost possessed the technology to do so and North Korea which succeeded in developing a nuclear weapon in recent years. There are currently international agreements in place to reduce the amount of nuclear weapons in existence because of the devastating human loss and environmental damages that can be caused if nuclear weapons are used in warfare. A nuclear war has the potential to wipe out all life on our planet!

Now check what you have just learnt by trying out the learning activity below!

Learning Activity 7

50 minutes

Answer the following questions on the spaces provided.

1. How does gamma radiation help in preserving fruit and vegetables?

____

____

____

____

2. Most people do not agree that fruits and vegetables should be exposed to gamma radiation. Explain why most people have such an opinion.

____

____

____

____

3. Most radioisotopes used in agriculture, industry and medicine have short half-lives either in hours, days or a few weeks. Explain why this is important.

____

____

____

____

4. A source of radiation is used in a paper factory in thickness gauging to produce paper of uniform thickness. This source of radiation emits beta particles. Explain why a source of alpha radiation is not suitable for this.

____

____

____

____

5. A certain radiopharmaceutical compound has a half-life of about 10 minutes. It is produced at a nuclear reactor about 50 minutes away from a hospital where a dose of 50mL is required to be used to diagnose a patient’s illness. What quantity of the radiopharmaceutical compound should be produced so that it can be immediately used once it arrives at the hospital?

6. Name the isotope of carbon that is used in radiocarbon dating. Explain where it is formed and how living things absorb it.

____

____

____

____

Thank you for completing learning activity 7. Now check your work. Answers are at the end of the module.

12.5.3 Nuclear Energy

Nuclear energy refers to the energy produced in modifying the composition of the nucleus of an atom. Nuclear energy is produced naturally through radioactivity. In the last 100 years, humans have been able to use technology to artificially change the atomic nucleus and produce energy on a larger scale than that produce by radioactivity.

Radioactivity is referred to as a **natural transmutation** where energy and newer nuclei are produced. **Artificial transmutation** refers to the use of technology to cause changes to the structure of a nucleus.

In this section of the module, we will look at the production of nuclear energy by artificial means. Nuclear reactors and nuclear weapons result from the use of technology to modify nuclear structures.

Nuclear energy is seen by many as the source of inexpensive, clean power, but because of the hazardous radiation emitted in producing that power and the radioactivity of the materials used, others feel that it may not be a viable energy alternative to the use of fossil fuels or solar energy.

The two main types of nuclear reactions that result in the release of large amounts of energy are **nuclear fission** and **nuclear fusion**.

A **fission reaction** is one where a large nucleus is split into fragments by collision with smaller particles. The energy that is released in a fission reaction comes from the force that holds the nucleus together. A **fusion reaction** is one in which two small atomic nuclei merge to form a heavier nucleus and, in most cases, an accompanying product such as a free nucleon. In almost all types of fusion reactions between light nuclei, a portion of their rest mass is converted into kinetic energy of the reaction products or into gamma rays.

Stars produce energy through a variety of fusion reactions. In main-sequence stars such as the Sun, the net effect of these reactions is to convert hydrogen nuclei (protons) into helium nuclei. The kinetic energy and gamma rays released in the process heat the stellar interior, maintaining it at the very high temperatures (greater than 10 million K) required to continue the fusion. Such conditions, where the thermal energy of the nuclei is sufficient to drive them together in spite of their electrostatic repulsion, are called **thermonuclear**.

A clear difference between fission and fusion is that an atomic bomb is the result of a nuclear fission and a hydrogen bomb is the result of a nuclear fusion.

Fission and Fusion

As radioisotopes undergo spontaneous nuclear changes and decay to more stable forms, they give off one or more of three types of emissions: alpha particles, beta particles, and gamma rays. The emission of alpha or beta particles converts one element into another by means of a change in nuclear charge. Gamma radiation is a form of nuclear energy dissipation.

A nuclear reaction happens when there is a change in the structure of the nucleus. Nuclear reactions can be classified as either, a **natural radioactive decay** or an artificial nuclear reaction.

The radioactive decay processes discussed in the previous section are examples of **spontaneous nuclear reactions** (natural radioactive decay). They occur naturally and no external trigger is required to set it off. In all of the nuclear reactions discussed earlier, there is release of enormous amounts of energy.

This section deals with **artificial (man-made) nuclear reactions**. Artificial nuclear reactions fall into two main categories. They can be either nuclear fission or nuclear fusion reactions.

Nuclear fission

Nuclear fission is a special type of nuclear reaction in which a heavy nucleus breaks up into two smaller nuclei or fragments.

Fission may occur spontaneously or by the bombardment of a nucleus with a particle such as a neutron or a proton or with gamma radiation.

Many different nuclei may undergo fission, but all have some common characteristics. Fission is a complex process, and it creates many different products which cannot be predicted. In addition to the two fragments, neutrons, beta particles, neutrinos, and gamma rays are also emitted in a fission process. Fission reactions involve splitting nuclei and producing more neutrons and a release of energy. In fission reactions, big atoms fall apart. Fission reactions make atoms smaller and more numerous.

Some nuclei, such as uranium-235, which contains 92 protons and 144 neutrons, are more suitable than others to undergo fission when bombarded by low-energy neutrons. For this reason, uranium-235 is used as the fissionable (fissile) material in the construction of a **nuclear reactor**. Each fission process causes additional neutrons to be emitted.

An example of a fission reaction caused by the neutron bombardment of uranium-236 is shown below.

$$\text{Uranium–236} \quad + \quad 1\,\text{neutron} \rightarrow \text{Xenon–143} \quad + \quad \text{Strontium–90} \quad + \quad 3\,\text{neutrons} \quad + \quad \text{energy}$$

$$^{236}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{143}_{54}\text{Xe} + {}^{90}_{38}\text{Sr} + 3({}^{1}_{0}\text{n}) + \text{energy}$$

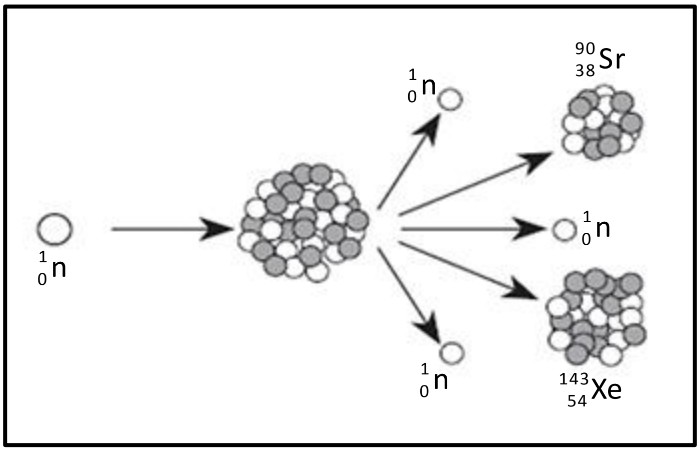


Figure 20 Nuclear fission of U-236

The neutrons produced by fission process of atoms may strike other atoms, causing them to split, which produces even more neutrons, which can then strike even more atoms causing a **chain reaction.**

In each generation, the number of fissionable nuclei increases even though some neutrons do not go on to strike another U-235 atom.

In a nuclear reactor the chain reaction is kept under control by absorbing excess neutrons with control rods of substances such as beryllium and cadmium. The uncontrolled chain reaction is called an **atomic bomb**.

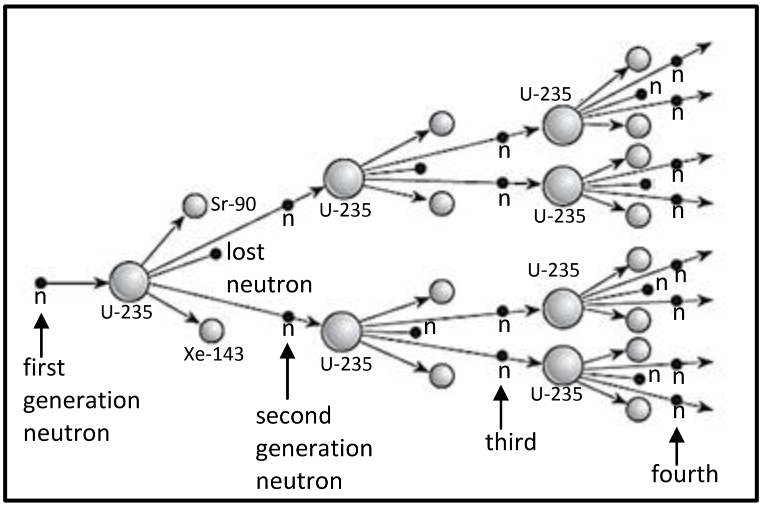


Figure 21 An uncontrolled fission chain reaction

More neutrons are produced than are absorbed and some of these neutrons can set off further fission reactions resulting in a chain reaction. A chain reaction occurs when one nuclear reaction produces particles which start off a chain of similar reactions.

The excess neutrons thus produced can cause more fission in the fissionable material, generating a chain reaction in the reactor.

The equation on the previous page shows that a heavy atom of uranium-235 is bombarded with a neutron resulting in the creation of krypton-91 and barium-142 plus 3 neutrons and large amount of energy (100, 000, 000, 000, 000 (10^{14}) Joules. This type of nuclear reaction is called **nuclear fission**. During fission reaction some of the mass is lost. The amount of energy released in this process is related to the lost mass.

The atom bomb dropped on Hiroshima that ended the Second World War, contained 64kg of uranium, of which 0.7kg underwent nuclear fission, and of this mass only 0.6 grams was transformed into energy. The 1.5 pounds of uranium that split that day yielded the same explosive energy as fifteen thousand (15,000) tons of explosive (TNT). Einstein showed this in his energy and matter equation as:

$$\mathbf{E = mc^2}$$

In an atomic bomb, the chain reaction happens so fast and is very hard to control. We can say that it is a wild or uncontrolled fission reaction.

Nuclear fusion

Nuclear fusion is another type of nuclear reaction where two light nuclei are merged together to form a heavier nucleus together and a release of energy. For example, if hydrogen-2 fuses with hydrogen-3, the nuclear reaction taking place is shown below:

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

The equation shows the formation of a helium nucleus, neutron plus energy by the merging of two hydrogen isotopes. Such a reaction is found in stars such as our sun which is an example of a **fusion reactor**.

So far, researchers are continuing research into fusion reactors to find ways of achieving high thermal energy for fusion reactions. If this is achieved, we can be able to produce energy that is renewable and far cleaner than any form of energy available. Currently, all the nuclear reactors in use today are all fission reactors.

Artificial Transmutation

An **artificial nuclear reaction** is caused by bombarding the nucleus with a projectile such as a proton, an electron, a neutron or other heavy nuclei such as nitrogen-14 (N-14), oxygen-16 (O-16), deuteron and an alpha particle among others.

Just as in radioactivity, we must ensure that the total atomic mass on the left is the same as the total atomic mass on the right of the nuclear equation.

Alpha bombardment

Rutherford designed in 1919, after the proton had been discovered, a series of experiments to probe further into the production of the proton. He bombarded nitrogen gas with 'bullets' of alpha particles resulting in the nuclear reaction shown below.

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

The nuclear reaction equation shows that the **transmutation** of nitrogen into oxygen had occurred. Using fast, high energy alpha particles as bullets to trigger nuclear reaction can sometimes result in the emission of neutrons.

For example, if we bombard beryllium nuclei with alpha particles, we produce carbon nuclei and fast moving neutrons.

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

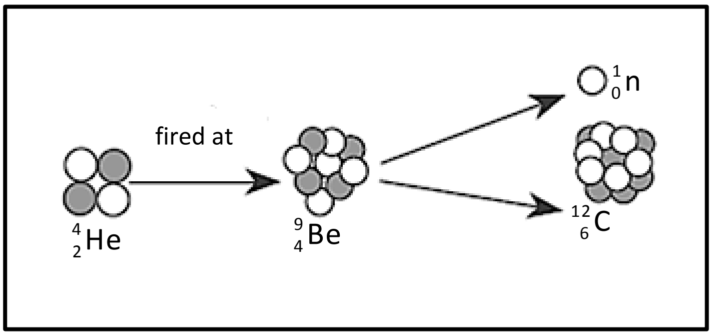


Figure 22 Bombardment of a nucleus by alpha particles producing a neutron.

Deuteron bombardment

Although it is almost impossible to turn lead into gold, **deuterons** can be used to make gold from mercury or platinum.

$$^{2}_{1}\mathrm{H} + {}^{199}_{80}\mathrm{Hg} \rightarrow {}^{197}_{79}\mathrm{Au} + {}^{4}_{2}\mathrm{He}$$

$$^{2}_{1}\mathrm{H} + {}^{196}_{78}\mathrm{Pt} \rightarrow {}^{197}_{78}\mathrm{Au} + {}^{1}_{0}\mathrm{n}$$

In both of these two reactions, the deuterons must be given high enough speed by a suitable accelerator to split into the nuclei of the target atoms. It costs a lot to use an accelerator, so it is cheaper to go and mine the gold.

Neutron bombardment

Since neutrons do not have any charge, they are ideal in using as projectiles to bombard nuclei for fission.

An example of neutron bombardment is shown below.

$$^{6}_{3}\text{Li} \quad + \quad ^{1}_{0}\text{n} \quad \rightarrow \quad ^{3}_{1}\text{H} \quad + \quad ^{4}_{2}\alpha$$

In this nuclear reaction, neutrons are given enough energy to split a lithium-6 nucleus into tritium (hydrogen-3) and an alpha (α) particle.

Now check what you have just learnt by trying out the learning activity below!

Learning Activity 8

50 minutes

Answer the following questions on the spaces provided.

1. Explain the term nuclear fission.

____

____

____

---

2. Explain the term nuclear fusion.

____

____

____

---

3. What is a chain reaction in nuclear fission?

____

____

____

---

4. Explain the difference between the nuclear fission reaction in a nuclear reactor and that in an atomic (fission) bomb.

____

____

____

____

____

5. Complete the following nuclear equations.

a) $^{11}_{5}B + ^{4}_{2}He \rightarrow ^{14}_{7}N + ?$

b) $^{23}_{11}Na + ^{1}_{0}n \rightarrow ?$

c) $^{27}_{13}Al + ^{2}_{1}H \rightarrow ^{4}_{2}He + ?$

d) $? + ^{4}_{2}He \rightarrow ^{42}_{20}Ca + ^{1}_{1}H$

e) $? + ^{1}_{0}n \rightarrow ^{27}_{12}Mg + ^{1}_{1}H$

f) $? + ^{4}_{2}He \rightarrow ^{12}_{6}C + ^{1}_{0}n$

Thank you for completing learning activity 8. Now check your work. Answers are at the end of the module.

Binding Energy

In an atomic nucleus, protons and neutrons are bunched together. We know from electrostatics that like charges repel and that the force between two like charges increases as we bring them close together. The nucleus however defies this rule. If protons are so close together in a nucleus, how is it that they do not repel each other and cause a nucleus to disintegrate?

The only explanation we can give is to say that there must be a force that exists in the nucleus only that acts over a small distance and is able to hold so many positive charges close together. We refer to this force as the **strong nuclear force**. Because it holds the nucleus together, we regard it as the strongest of the fundamental interactions of matter.

Since energy and force go hand-in hand, where there is a force there is also energy involved. A large amount of energy is contained within the nucleus of an atom. This energy is called **binding energy**.

The **total binding energy of a nucleus** is the energy required to separate it into its constituent neutrons and protons. Conversely, when neutrons and protons are combined to form nuclei, energy equal in amount to the binding energy is released in the process.

Some of the binding energy can be released either by splitting an atom or by merging together two atoms. In a nuclear reaction, changes occur in the nucleus of an atom. Consequently, a great amount of energy is released. The energy released by nuclear reactions is much larger, per gram of explosive material, than the energy released by chemical explosions.

As the nuclear force is so strong, nuclear binding energies are typically a million times greater than the electrostatic energies binding electrons to the nucleus in an atom or binding atoms together in molecules.

Mass defect

When accurate measurements of the masses of nucleons and nuclei are made, a significant discrepancy is seen. **The mass of a nucleus is found to be always less than the combined individual masses of its constituent nucleons**. This is referred to as the **mass defect**.

For example, the mass of a deuterium nucleus ($^{2}_{1}H$) is 3.34364×10^{-27}kg. However, the sum of the masses of the individual proton and neutron is 3.34760×10^{-27}kg. There is a mass defect of 3.96×10^{-30}kg, about 0.1183 percent missing.

When energy is given off in the formation of a nucleus, the mass of the nucleus decreases compared to the sum of the masses of the free neutrons and protons from which it is formed. The difference in mass is assumed to have been converted to energy using Einstein's equation;

$$\mathbf{E = mc^2}$$

This equation relates to the conversion of mass to energy and vice versa. Where **E** is the energy released when a nucleus is formed and can also be the energy that is required to split the nucleus. **m** is the mass defect (difference) while **c** stands for the speed of light which 3.0 $\times 10^8 ms^{-1}$.

If the nucleus were to be split apart, the equation would also provide information about how much energy is being released.

For example, when a neutron and proton combine to form the nucleus of a deuterium (heavy hydrogen) atom, a gamma ray is emitted, carrying away energy. The same amount of energy would have to be supplied from the outside in order to separate a deuteron again into a neutron and proton. Accordingly, the mass of a deuteron is less than the combined masses of a neutron and proton by about 0.1 percent. This amount, multiplied by $\mathbf{c^2}$, is equivalent to the deuteron's binding energy.

Nuclear Reactor

A **nuclear reactor** is a device in which a controlled nuclear reaction takes place. The most common nuclear reactors are purposely made to contain nuclear fission reactions. In such reactors, the fission reaction is initiated by the absorption of a neutron in a heavy nucleus such as uranium-235 (U-235). The process produces additional neutrons that can be used to induce further fissions, thereby propagating the chain reaction.

When the reactor materials are appropriately adjusted, it is possible for the chain reaction to be self-sustaining. Such a reactor is described as **critical**. If there are insufficient neutrons being produced to sustain the process, then the reactor is **subcritical**. Conversely, if too many neutrons are being produced, the reaction rate increases with time and the reactor is called **supercritical**.

Nuclear reactors are most commonly used to produce electric energy, although they are occasionally used as sources of thermal energy for heating. They are also designed as sources of neutrons used in research or for the transmutation of elements. Reactors designed to produce materials for nuclear weapons by transmutation are called **production reactors.**

Numerous devices use nuclear processes other than fission as their energy source, although these devices are not called nuclear reactors. For instance, power supplies on spacecraft use the energy from radioactive decay, and hence are called **radioisotope power supplies**.

Similarly, devices based on the fusion process are called **thermonuclear** or **fusion** reactors.

Nuclear Fission reactor

A fission reactor is composed of several main parts.

1. **Fuel rods** – These contain the material in which nuclear fission takes place. Most fuel rods are made of fissionable materials such as Uranium or Plutonium isotopes.

2. **Moderator** – the main function of the moderator is to absorb neutrons and slow down high speed neutrons so that they are able to cause fission to occur.
   In the reactor above, the moderator is heavy water. Other materials such as graphite and molten sodium are also used in some types of reactors as moderators.

3. **Control rods** – the purpose of the control rods is to stop a chain reaction from going out of control. The control rods are made of steel with traces of boron and cadmium which are good materials for absorbing neutrons. To increase the rate of fission, the control rods are lifted. To decrease the rate of fission, the control rods are inserted between the fuel rods.

4. **Coolant** – this is a material that is used to transfer heat from the reactor. Without the coolant the reactor would melt due to the immense heat produced. Such an event is called a **meltdown**. In most cases the coolant transfers its heat to another substance such as water which turns to steam which turns turbines for producing electricity or for other uses. Materials commonly used as coolants are heavy water, liquid sodium and helium gas. Once a material is used as a coolant, it becomes radioactive and depending on its half-life has to be disposed or stored safely.

5. **Reactor shield** – most reactors have to be housed in thick concrete vessels. These concrete vessels help to shield workers near a reactor from harmful radiation. Another material that can be used as a shield is lead.

All these five (5) parts are shown in figure 23 on the next page. The first four (4) parts of a nuclear reactor are part of the **reactor core**.

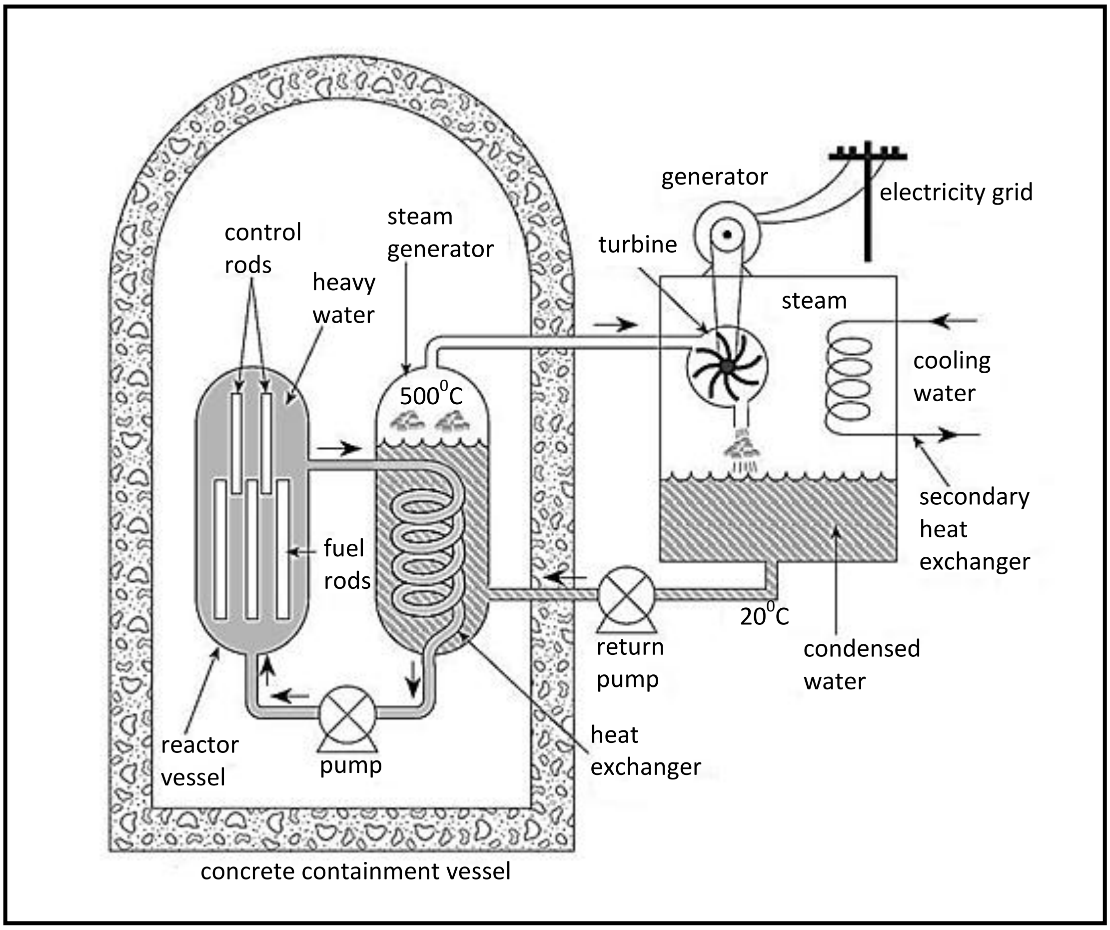


Figure 23 Schematic diagram of a typical pressurized water thermal reactor in a nuclear power station.

Basically there are two types of fission power reactors, the **thermal reactor** and the **fast-breeder** reactor which is more modern.

One of the main problems with fission nuclear reactor is the safe storage and containment of the radioactive waste they produce. This requires adherence to so many safety-precautions rules. Today, they are removed and stored deep underground in stable parts of the earth's crust.

Fusion reactors

In fusion reactions, small nuclei or little atoms come together and release much more energy and make atoms bigger but less numerous. For example, when deuterium, a hydrogen isotope that has one proton and one neutron is fused with tritium, another hydrogen isotope having one proton and two neutrons, a helium nucleus is formed and a neutron plus an enormous amount of energy are also produced.

In order for the particles to come close enough to fuse together, the deuterium or tritium atoms must have very high kinetic energy, sufficient to overcome the Coulomb repulsion forces. Such high speed can be achieved by heating the gas to a temperature of 100 million degree centigrade. High temperatures and pressures like those found inside the Sun are needed to sustain nuclear fusion. These pause two major problems associated with this:

- How do we reach this high temperature and maintain it?
- How do we contain the fuel, since most containers would melt well before 100 million degrees centigrade is reached?

For the construction of fusion power reactors, the reactions mentioned earlier involving deuterium and tritium seem to be promising. There is a vast supply of deuterium available in ordinary water, particularly in sea water. Therefore, there is no scarcity of fuel for fusion reactors. The sun is a classic example of fusion reactor. At such high temperatures, gas contains electrons and positive ions and is called 'plasma'. Fusion reactor radiates alpha particles which is a clean stable helium atom.

Now check what you have just learnt by trying out the learning activity below!

Learning Activity 9

50 minutes

Answer the following questions on the spaces provided.

1. What is the binding energy of a nucleus?

____
____
____

2. What is the mass defect and how is energy related to it?

____
____
____
____
____

3. What is a nuclear reactor?

____
____
____

4. State two (2) differences between nuclear fusion and nuclear fission reactions.

(i) ____
____
____

(ii) ____

____

____

5. At any one time, a nuclear fission reactor can be described as critical, subcritical or supercritical. Explain the terms critical, subcritical and supercritical in relation to the production of neutrons in a nuclear fission reactor.

____

____

____

____

____

____

6. Name the part of the nuclear fission reactor that is responsible for:

a) controlling temperature and transferring heat produced.

____

b) slowing high speed neutrons and ensure that fission occurs.

____

c) controlling the rate of fission reactions.

____

d) stopping harmful radiation from escaping from the reactor core.

____

7. Assuming technical problems could be overcome, state two (2) advantages of using a fusion reactor to produce electricity.

____

____

____

____

____

Thank you for completing learning activity 9. Now check your work. Answers are at the end of the module.

NOW REVISE WELL USING THE MAIN POINTS ON THE NEXT PAGE.

SUMMARY

You will now revise this module before doing **ASSESSMENT 5**.
Here are the main points to help you revise. Refer to the module topics if you need more information.

- The number of protons in a nucleus is given by the atomic number, while the total number of nucleons is given by the mass number.
- Atoms of the same element with different numbers of neutrons are called isotopes of that element.
- Many elements have naturally occurring unstable radioisotopes.
- In alpha decay an unstable nucleus decays by emitting an alpha particle (α-particle).
- In beta decay, a neutron changes into a proton and a high-energy electron that is emitted as a beta particle (β-particle).
- In positron decay, a positron—the antiparticle of the electron—is emitted.
- When a positron and an electron collide, their total mass is converted into energy in the form of two gamma-ray photons.
- In gamma decay a gamma ray (γ) is emitted from a radioactive isotope.
- The time it takes for half the mass of a radioactive parent isotope to decay into its daughter nuclei is the half-life of the isotope.
- Artificial radioisotopes are produced in two main ways: in a nuclear reactor or in a cyclotron.
- X-rays are a form of electromagnetic radiation that lies between ultraviolet and gamma radiation on the electromagnetic spectrum.
- X-rays are used for the diagnosis of medical problems and injuries, and for therapeutic purposes such as the treatment of certain tumours.
- The modern X-ray tube is based upon the 1913 design by William Coolidge, which used a hot cathode and permitted a stable and controllable continuous production of X-rays.
- The CAT scan was independently conceived by Allan McLeod Cormack and Godfrey Hounsfield.
- X-rays are emitted when high-energy electrons strike a target.
- There are two processes by which X-rays can be produced: characteristic X-rays and Bremsstrahlung.
- X-rays are often categorised by the terms ‘hard’ X-rays and ‘soft’ X-rays, which are descriptive terms indicating the relative penetrating ability of the X-ray beam.
- A fissioning nucleus breaks into two unequal parts, creating a lighter fragment and a heavier fragment.

We hope you have enjoyed studying this module. We encourage you to revise well and complete Assessment 5.

NOW YOU MUST COMPLETE ASSESSMENT TASK 5 AND RETURN IT TO THE PROVINCIAL CENTRE CO-ORDINATOR

Answers to Learning Activities 1 - 9

Learning Activity 1

1. a) A nucleon is term used to describe any particle that is found inside the nucleus of an atom.
   b) An isotope is any atom of an element with the same number of protons (atomic number) but different number of neutrons (mass number).
   c) A nuclide is any form of an element.
   d) Unified atomic mass is a unit for measuring the mass of atoms and subatomic particles.
2.

ISOTOPE	Number of protons	Number of neutrons	Number of electrons
$^{14}_{6}\text{C}$	6	8	6
$^{93}_{38}\text{Sr}$	38	55	38
$^{216}_{84}\text{Po}$	84	132	84
$^{228}_{88}\text{Ra}$	88	140	88
$^{241}_{95}\text{Am}$	95	146	95

3. Some isotopes are unstable because they either have too many protons or too many neutrons.

Learning Activity 2

1. a) alpha radiation $^{4}_{+2}\text{He}$, $^{4}_{2}\alpha$, α
   b) beta radiation $^{0}_{-1}\text{e}$, $^{0}_{-1}\beta$, β
   c) gamma radiation γ

2. a) gamma
   b) alpha
   c) gamma
   d) beta

e) beta and gamma

f) alpha

3. a) alpha radiation deflected downward

   b) beta radiation deflected upward

   c) gamma radiation is not deflected

4. The ionizing ability of radiation is harmful to living organisms.

5. a) fluorescence

   b) ionization ability

   c) ionization ability

   d) ionization ability

Learning Activity 3

1. A nuclear transmutation is a change in the composition of an unstable nucleus by emitting radiation.

2. A radioactive decay is a chemical change because it results in the formation of a new substance (element).

3. a) In alpha decay, the atomic number decreases by 2 while the mass number decreases by 4.

   b) In beta (electron) decay, the atomic number increases by 1 while the mass number is unchanged.

   c) In positron decay, the atomic number decreases by 1 while the mass number is unchanged.

   d) In gamma decay, the atomic number and mass number are unchanged.

4. a) beta decay

   b) positron decay

   c) alpha decay

5. a) $w = 30$

   b) X = Tl or Thallium

   c) $y = 27$

   d) $L = 0$

      $M = -1$

6. a) $^{224}_{88}\text{Ra} \rightarrow {}^{220}_{86}\text{Rn} + {}^{4}_{+2}\text{He}$

   Daughter nucleus: Radon-220

   b) $^{214}_{82}\text{Pb} \rightarrow {}^{214}_{83}\text{Bi} + {}^{0}_{-1}\text{e}$

   Daughter nucleus: Bismuth-214

   c) $^{227}_{89}\text{Ac} \rightarrow {}^{227}_{90}\text{Th} + {}^{0}_{-1}\text{e}$

   Daughter nucleus: Thorium-227

   d) $^{213}_{83}\text{Bi} \rightarrow {}^{209}_{81}\text{Tl} + {}^{4}_{+2}\text{He}$

   Daughter nucleus: Thallium-209

7. Z = 90, A = 232

8. Bi

9. $^{A-9}_{Z-4}\text{Y}$

Learning Activity 4

1. A decay series is a successive chain of decays until a stable daughter nucleus is formed.

2. The two arrows drawn from $^{218}_{84}\text{Po}$, suggest the two possible (alternative) decays that can occur after $^{218}_{84}\text{Po}$ is formed.

3. a) alpha (α) decay
   b) beta (β^-) decay
   c) beta (β^+) decay

4. A nuclide of Polonium is formed three (3) times according to the decay series.

5. The nuclides of lead formed in this decay series are lead-214, lead-210, lead-206.

6. Elements that are have nuclides appearing twice or more are uranium, thorium, radon, polonium, bismuth and lead.

Learning Activity 5

1. a) Radioactivity is the spontaneous emission of energy in the form of particles or waves (electromagnetic radiation), or both, from the unstable atomic nucleus of certain elements.

b) The Becquerel is a unit used when measuring the rate of decay of a radioactive substance. It is defined as the number of nuclear disintegrations per second.

c) The Curie is also a unit used when measuring the rate of decay of a radioactive substance. It is defined as the number of nuclear disintegrations per second in 1g of radium.

d) The half-life of a radioisotope is the amount of time taken for half of a sample of that radioisotope to decay.

e) Exponential decay is the mathematical model used to describe radioactivity over a period of time.

2.	a)	Bismuth-210	5.01 days
	b)	Uranium-234	245, 000 years
	c)	Thorium-234	24.1 days
	d)	Radon-222	3.8 days
	e)	Polonium-218	3.1 minutes
	f)	Polonium-214	164 microseconds
	g)	Carbon-14	5 730 years

3. a) 10g

   b) 5g

   c) 1.25g

Learning Activity 6

1. The decay constant is a constant of proportionality that relates the activity of a sample to the number of radioactive nuclei in a sample.

2. a) 9.96 min
   b) 14.91g
   c) 6.88×10^{23} atoms

3. a) 0.032 hr^{-1}
   b) 21.6 hr

4. a) $0.0224\ s^{-1}$ and $1.341\ min^{-1}$

   b) i) 5g ii) 1.25g iii) 3×10^{-5}g

Learning Activity 7

1. Gamma radiation slows down the ripening process and stops fruits and vegetables from sprouting.

2. Because gamma radiation can change the structure of molecules in fruits and vegetables sometimes forming carcinogenic (cancer forming) molecules.

3. Short half-lives are required so that little of the radioactivity remains after the radioisotope is used.

4. Alpha radiation has a low penetrative power.

5. 1600 mL

6. The carbon isotope used is carbon-14. It is formed in the atmosphere by the reaction between cosmic rays and nitrogen-14. Living things absorb carbon-14 through the carbon cycle.

Learning Activity 8

1. Nuclear fission is the splitting of a nucleus by bombarding it with a high speed particle such as a neutron which results in the release of energy.

2. Nuclear fusion is the joining of two nuclei accompanied by the release of large amounts of energy.

3. In nuclear fission, a chain reaction is one where the products of a nuclear fission reaction produce further fission reactions.

4. In a nuclear fission reactor, the chain reaction is controlled whereas in an atomic bomb, the chain reaction is uncontrolled.

5. a) ${}^{1}_{0}n$

   b) ${}^{24}_{11}Na$

   c) ${}^{25}_{12}Mg$

   d) ${}^{39}_{19}K$

   e) ${}^{27}_{13}Al$

f) $^{9}_{4}\mathrm{Be}$

Learning Activity 9

1. The binding energy of a nucleus is the amount of energy required to separate a nucleus into its component nucleons.

2. The mass defect is the difference in the sum of the masses of nucleons and the mass of a nucleus. The mass of a nucleus is always slightly less than that of the sum of the masses of its component nucleons. This difference in mass is thought to have been converted into energy.

3. A nuclear reactor is a device that can contain a nuclear reaction and transfer the energy that is produced during nuclear reactions.

4. State any two of the following differences between nuclear fission and nuclear fusion.

   (i) Fission is the splitting of nuclei, while fusion is the joining of nuclei.
   (ii) Fusion requires more energy to begin with; fission does not require as much energy to start.
   (iii) Fusion reactions release more energy than fission reactions.

5. In a nuclear fission reactor, a critical state occurs when the number of neutrons produced is sufficient to sustain a controlled chain reaction. A subcritical state occurs when the number of neutrons produced is not sufficient to sustain a controlled chain reaction. A supercritical state occurs when the number of neutrons produced is greater than necessary leading to a chain reaction which is uncontrolled.

6. a) coolant
   b) moderator
   c) control rods
   d) shielding

7. State any two (2) of the following advantages of electricity production using a nuclear fusion reactor.

   (i) Fuel for fusion reactor is hydrogen which is relatively abundant.
   (ii) Waste products of a fusion reactor are not very harmful to the environment.
   (iii) Fusion reactions result in more energy than fission reactions.

If you have queries regarding the answers, then please visit your nearest FODE provincial centre and ask a distance tutor to assist you.

References

CHANG, R, (2000), CHEMISTRY e-Text, 6th Edition, MCGRAW-HILL Inc, United States of America

GIANCOLI, D.C., (1985), PHYSICS PRINCIPLES WITH APPLICATIONS, 2nd Edition, PRENTICE-HALL, LONDON, United Kingdom

POPLE, S, (1982), EXPLAINING GCSE PHYSICS, OXFORD UNIVERSITY PRESS, OXFORD, United Kingdom

TSOKOS, K.A., (2008) PHYSICS FOR IB DIPLOMA, 5th EDITION, CAMBRIDGE UNIVERSITY PRESS, CAMBRIDGE, United Kingdom

WALDING, R. et al, (2004), NEW CENTURY PHYSICS, 2nd EDITION, OXFORD UNIVERSITY PRESS, MELBOURNE, Australia

YONG, P.L., (2006), PACIFIC PHYSICS A LEVEL, Volume 2, PANPAC EDUCATION LTD, SINGAPORE

FODE PROVINCIAL CENTRES CONTACTS

PC NO.	FODE PROVINCIAL CENTRE	ADDRESS	PHONE/FAX	CUG PHONES	CONTACT PERSON		CUG PHONE
1	DARU	P. O. Box 68, Daru	6459033	72228146	The Coordinator	Senior Clerk	72229047
2	KEREMA	P. O. Box 86, Kerema	6481303	72228124	The Coordinator	Senior Clerk	72229049
3	CENTRAL	C/- FODE HQ	3419228	72228110	The Coordinator	Senior Clerk	72229050
4	ALOTAU	P. O. Box 822, Alotau	6411343 / 6419195	72228130	The Coordinator	Senior Clerk	72229051
5	POPONDETTA	P. O. Box 71, Popondetta	6297160 / 6297678	72228138	The Coordinator	Senior Clerk	72229052
6	MENDI	P. O. Box 237, Mendi	5491264 / 72895095	72228142	The Coordinator	Senior Clerk	72229053
7	GOROKA	P. O. Box 990, Goroka	5322085 / 5322321	72228116	The Coordinator	Senior Clerk	72229054
8	KUNDIAWA	P. O. Box 95, Kundiawa	5351612	72228144	The Coordinator	Senior Clerk	72229056
9	MT HAGEN	P. O. Box 418, Mt. Hagen	5421194 / 5423332	72228148	The Coordinator	Senior Clerk	72229057
10	VANIMO	P. O. Box 38, Vanimo	4571175 / 4571438	72228140	The Coordinator	Senior Clerk	72229060
11	WEWAK	P. O. Box 583, Wewak	4562231/ 4561114	72228122	The Coordinator	Senior Clerk	72229062
12	MADANG	P. O. Box 2071, Madang	4222418	72228126	The Coordinator	Senior Clerk	72229063
13	LAE	P. O. Box 4969, Lae	4725508 / 4721162	72228132	The Coordinator	Senior Clerk	72229064
14	KIMBE	P. O. Box 328, Kimbe	9835110	72228150	The Coordinator	Senior Clerk	72229065
15	RABAUL	P. O. Box 83, Kokopo	9400314	72228118	The Coordinator	Senior Clerk	72229067
16	KAVIENG	P. O. Box 284, Kavieng	9842183	72228136	The Coordinator	Senior Clerk	72229069
17	BUKA	P. O. Box 154, Buka	9739838	72228108	The Coordinator	Senior Clerk	72229073
18	MANUS	P. O. Box 41, Lorengau	9709251	72228128	The Coordinator	Senior Clerk	72229080
19	NCD	C/- FODE HQ	3230299 Ext 26	72228134	The Coordinator	Senior Clerk	72229081
20	WABAG	P. O. Box 259, Wabag	5471114	72228120	The Coordinator	Senior Clerk	72229082
21	HELA	P. O. Box 63, Tari	73197115	72228141	The Coordinator	Senior Clerk	72229083
22	JIWAKA	c/- FODE Hagen		72228143	The Coordinator	Senior Clerk	72229085

FODE SUBJECTS AND COURSE PROGRAMMES

GRADE LEVELS	SUBJECTS/COURSES
Grades 7 and 8	1. English
	2. Mathematics
	3. Personal Development
	4. Social Science
	5. Science
	6. Making a Living
Grades 9 and 10	1. English
	2. Mathematics
	3. Personal Development
	4. Science
	5. Social Science
	6. Business Studies
	7. Design and Technology- Computing
Grades 11 and 12	1. English – Applied English/Language& Literature
	2. Mathematics - Mathematics A / Mathematics B
	3. Science – Biology/Chemistry/Physics
	4. Social Science – History/Geography/Economics
	5. Personal Development
	6. Business Studies
	7. Information & Communication Technology

REMEMBER:

- For Grades 7 and 8, you are required to do all six (6) subjects.
- For Grades 9 and 10, you must complete five (5) subjects and one (1) optional to be certified. Business Studies and Design & Technology – Computing are optional.
- For Grades 11 and 12, you are required to complete seven (7) out of thirteen (13) subjects to be certified.

Your Provincial Coordinator or Supervisor will give you more information regarding each subject and course.

GRADES 11 & 12 COURSE PROGRAMMES

No	Science	Humanities	Business
1	Applied English	Language & Literature	Language & Literature/Applied English
2	Mathematics A/B	Mathematics A/B	Mathematics A/B
3	Personal Development	Personal Development	Personal Development
4	Biology	Biology/Physics/Chemistry	Biology/Physics/Chemistry
5	Chemistry/ Physics	Geography	Economics/Geography/History
6	Geography/History/Economics	History / Economics	Business Studies
7	ICT	ICT	ICT

Notes: You must seek advice from your Provincial Coordinator regarding the recommended courses in each stream. Options should be discussed carefully before choosing the stream when enrolling into Grade 11. FODE will certify for the successful completion of seven subjects in Grade 12.

CERTIFICATE IN MATRICULATION STUDIES		
No	**Compulsory Courses**	**Optional Courses**
1	English 1	**Science Stream:** Biology, Chemistry, Physics
2	English 2	**Social Science Stream:** Geography, Intro to Economics and Asia and the Modern World
3	Mathematics 1	
4	Mathematics 2	
5	History of Science & Technology	

REMEMBER:

You must successfully complete 8 courses: 5 compulsory and 3 optional.