RADIOACTIVITY

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Objectives

By the end of the topic the learner should be able to:

(a) Define radioactivity, half-life, radioisotopes and nuclides.

(b) State the types of radioactivity, name the particles emitted during radioactive decay and state their properties.

(c) Carry out simple calculations involving half-life (t- ½).

(d) Write balanced nuclear equations.

(e) Distinguish between nuclear fission and fusion.

(f) State the uses of some radioisotopes and dangers associated with radioactivity.

Organizer

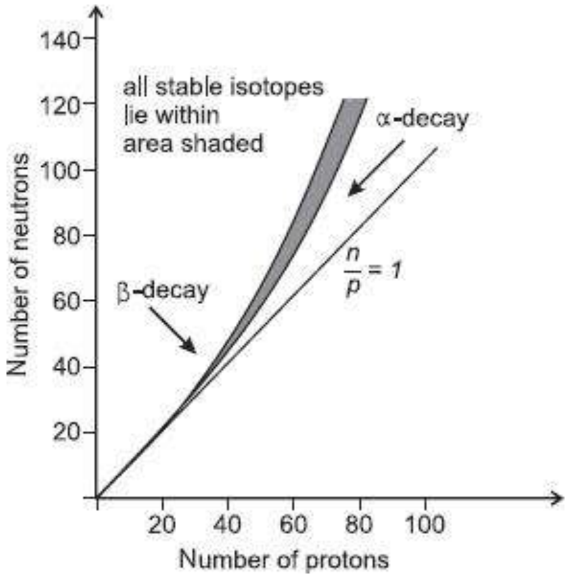
RADIOACTIVITY

Stability of Isotopes of Elements

A particular nucleus of an atom characterised by its protons and neutrons is known as a nuclide.

Nuclides can either be stable or unstable. Most stable nuclides have a neutron/proton(n/p) ratio of about 1 : 1. For example, $^{20}_{40}Ca$ has 20 neutrons and 20 protons, hence the n/p ratio is 20 : 20= 1 : 1.

For nuclides of high atomic number, the n/p ration increases progressively up to about 1.6 : 1 which is still within the stability region. Above this value the nucleus becomes too large and unstable.



The unstable nuclide normally undergoes some changes by emitting radiation in form of particles and energy. Such emissions results in the production of new nuclides of completely different composition.

Radioactivity as a Nuclear Reaction

Radioactivity is the process where an unstable nuclide breaks up to yield another nuclide of different composition with emission of particles and energy.

Substances, which undergo radioactivity, are said to be **radioactive**. Isotopes, which are radioactive, are known as **radioisotopes**.

The spontaneous disintegration of radioactive nuclides is known as **radioactive decay**. **Radioactivity is a nuclear process and not a chemical reaction.**

Differences between chemical and nuclear reactions

Nuclear Reaction	Chemical Reaction
1. Takes place within the nucleus and involves neutrons and protons.	Takes place on the outer energy levels containing the valence electrons. Does not involve protons and neutrons.
2. Releases large amounts of heat energy.	The heat energy released is much less.
3. Not affected by environmental factors such as temperature.	Are affected by environmental factors such as temperature and pressure.

Types of Radioactivity

There are two types of radioactivity namely **natural** and **artificial**.

Natural radioactivity occurs when radioactive nuclei **split spontaneously** yielding a new nuclide with the emission of radiation and energy.

For example, the nucleus of uranium– 238 undergoes natural radioactive decay to form Thorium – 234 and some radiation.

Artificial radioactivity occurs when large stable nuclides are **bombarded with fast moving high-energy particles**. In the process, the nuclides split into relatively smaller nuclei with emission of radiation and energy.

Types, Characteristics and Properties of radiations

When radioactive nuclides disintegrate, they emit radiations namely alpha particles (α), beta (β) and gamma (γ).

Characteristics of Radiations

Alpha radiations are particles which are positively charged helium nuclei, He^{2+}. They are represented as ${}^{4}_{2}He^{+}$ in nuclear equations. Alpha particles have an electrical charge of 2^{+}. They are the heaviest of the three radiations.

Beta radiations are particles which are negatively charged. They are represented as ${}^{0}_{-1}e$. They are electrons, which originate from within the nucleus and not from the outer energy levels. They are formed when a neutron changes into a proton within the nucleus.

$$\underset{\text{neutron}}{{}^{1}_{0}n} \longrightarrow \underset{\text{proton}}{{}^{1}_{1}p} + \underset{\text{electron}}{{}^{0}_{-1}e}$$

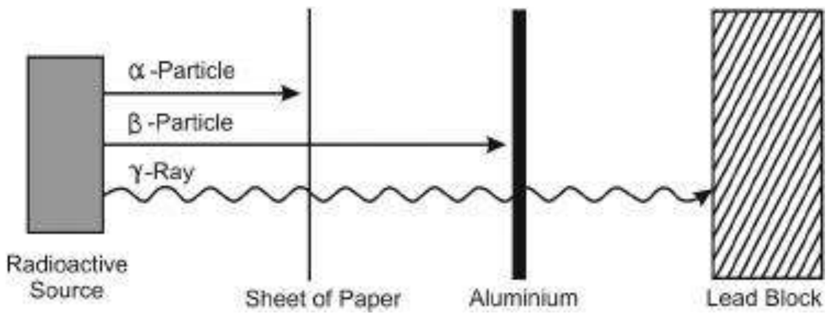
The –1 is not an atomic number. It represents the charge on the particles. Beta particles have an electrical charge of $^{-}1$.

Gamma radiations are high energy rays. They do not have an electrical charge. They are not emitted on their own but normally accompany the emission of alpha or beta particles.

Properties of Radiations

Penetrating power

Alpha particles have very **low penetrating** power. They do not pass through a sheet of paper. The have a range of only a few centimetres in air.

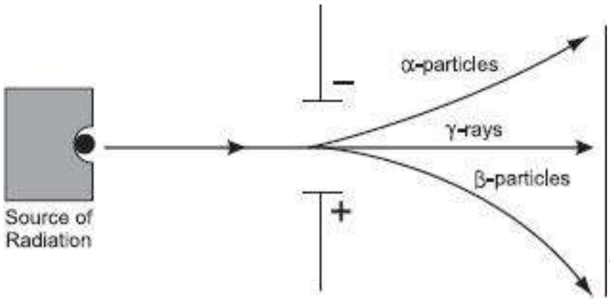


Beta particles have **higher penetrating power**. They can pass through a sheet of paper but are stopped by a sheet of aluminium foil.

***Gamma* rays** have the **highest penetrating power.** They pass through a sheet of paper and a sheet of aluminium. They are however stopped by a thick lead block.

Deflection by an Electric Field

Alpha particles are **positively charged**. They are therefore **attracted to the negative plate** in an electric field. Since they are **heavy** they are only **slightly deflected**.



Beta particles are **negatively charged** and so are **deflected to the positive plate** in an electric field. The **deflection is greater** than that of alpha particles due to their much **smaller masses**.

Gamma rays do not have a charge and are therefore **unaffected** by an electric field.

Ionising Effect of Radiations

Alpha particles have **very high ionising** power. They produce a **large number of ions** as they pass through gases due to their slow speed and high charge. Their slow speed enables the alpha particles to be in contact with target atoms for a longer time.

Beta particles have **lower ionising power** and produce fewer ions in gases.

Gamma rays have **very low ionising** power.

Radioactive Decay and Half-Life

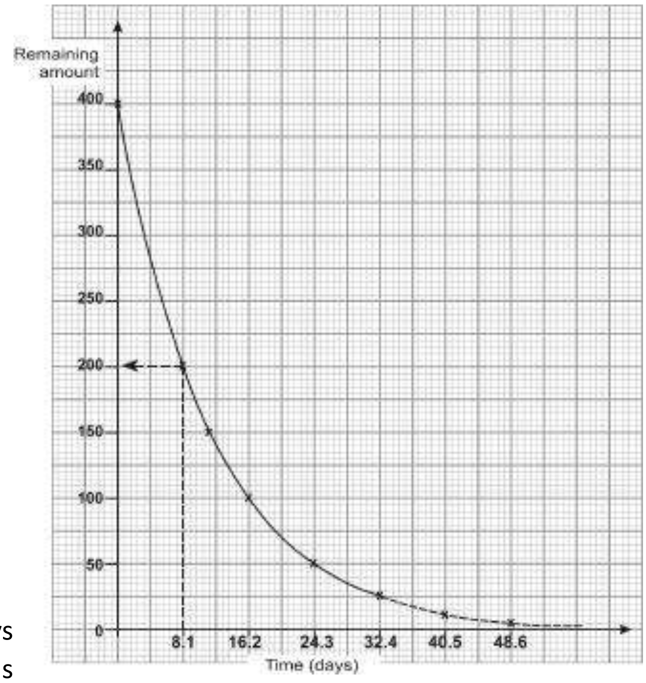
When a radioactive nuclide decays, a new nuclide is formed. As disintegration proceeds, fewer and fewer unstable atoms remain.

The Table below shows the radioactive decay for a sample of 400 g of iodine – 131

Decay of iodine -131

Time (days)	Mass (g) of radioactive iodine remaining
0	400
8.1	200
16.2	100
24.3	50
32.4	25

A graph of the data given is shown alongside.



From the graph it can be seen that after every 8.1 days the amount of substance remaining is half the previous amount.

The fractions of the original amount remaining after:

(i) 8.1 days is $\frac{1}{2}$

(ii) 16.2 days if $\frac{1}{4}$

(iii) 24.3 days is $\frac{1}{8}$

From the graph, it is also observed that the remaining amount never reduces to zero. The time taken for the mass to reduce to half the previous value is a constant, i.e., 8.1 days. This constant value is referred to as the half-life. It is denoted by $t\frac{1}{2}$.

The half-life *of a radioactive isotope is the time taken for a given mass or number of nuclides to decay to half its original mass or number.*

From the sample of 400 g iodine – 131 given in the example, the amount remaining after the first half-life (8.1 days) will be 200 g. After the second half-life (16.2 days) it will be 100g. This can be illustrated as shown.

$$400\text{ g} \xrightarrow[\textit{8.1 days}]{\textit{1}^{st}\textit{ half-life}} 200\text{ g} \xrightarrow[\textit{8.1 days}]{\textit{2}^{nd}\textit{ half-life}} 100\text{ g} \xrightarrow[\textit{8.1 days}]{\textit{3}^{rd}\textit{ half-life}} 50\text{ g}$$

The amount remaining after the first half-live is half the previous amount. The remaining amount after successive nuclide decay can be worked out by using the formula;

Remaining amount = $\left(\frac{1}{2}\right)^n$ × original amount, where n is the number of half-lives undergone. For example the remaining amount after 24.3 days (3 half-lives) is $\left(\frac{1}{2}\right)^3 \times 400 = \frac{1}{8} \times 400 = 50$ g.

Given the remaining amount, the original amount can also be determined. For example: if 3g of $^{257}_{103}Lr$ Lr whose half -life is 8 seconds remain after undergoing radioactive decay for 32 seconds.

The number of half-life = $\frac{32}{8} = 4$

Using the formula :– $\left(\frac{1}{2}\right)^4 \times$ original amount (x) = 3

Original amount $\times \frac{1}{16} = 3$

$= 48$ g

Alternatively, the original amount can be found using a step by step method thus;

$$3\text{ g} \xrightarrow[\textit{8 s}]{\textit{4}^{th}\textit{ half-life}} 6\text{ g} \xrightarrow[\textit{8 s}]{\textit{3}^{rd}\textit{ half-life}} 12\text{ g} \xrightarrow[\textit{8 s}]{\textit{2}^{nd}\textit{ half-life}} 24\text{ g} \xrightarrow[\textit{8 s}]{\textit{1}^{st}\textit{ half-life}} 48\text{ g}$$

The original amount is 48 g.

Each radioactive isotope decays at its own rate and therefore has its own half- life. Half-life $\left(t\frac{1}{2}\right)$ range from fraction of a second to millions of years. For example:

Nuclide	**half-life**
$^{212}_{84}Po$	2.96×10^{-7} seconds
$^{257}_{103}Lr$	8 seconds
$^{234}_{91}Pa$	1.14 minutes
$^{234}_{90}Th$	24.5 days
$^{1}_{1}H$	12.3 years
$^{14}_{6}C$	5570 years
$^{234}_{92}U$	4.5×10^{9} years

The shorter the half-life, the faster the rate of decay of the nuclide. The longer the half-life, the slower the rate of decay of the nuclide. The rate of radioactive decay is unaffected by any chemical or physical change.

The half-life of radioactive isotopes is one of the factors used to determine their application. For example, carbon-14 is used to determine the age of dead organic matter. The process is known as **carbon-dating**. The carbon in plants which is taken up during photosynthesis contains a small portion of radioactive carbon-14. When the plant dies, the carbon-14 in the dead plant continues decaying hence the amount decreases. Carbon-14 has half-life a of about 5,600 years therefore by determining the carbon content in the dead material it is mathematically possible to determine the age of the sample.

Sodium-20 with a half-life of 0.3 seconds is used to detect leakages because it has a short half-life.

Nuclear Reactions

When an alpha particle is emitted from the nucleus, both the atomic number and the mass number of the nuclide decrease. A new nuclide is formed as represented by the following equation

$$^{234}_{91}Pa \longrightarrow \, ^{229}_{89}Ac + \, ^{4}_{2}He$$

The equation above is referred to as a nuclear equation.

The sum of the mass number on the right hand side of the equation is equal to the mass number of the left hand side. The sum of proton numbers on the right hand side equals the number of protons on the left hand side.

When a beta particle is emitted, the atomic number increases by one and the mass number remains constant. This is because:

(i) During beta emission, a neutron spontaneously changes into a proton and emits an electron. That is:

$$^{1}_{0}n \longrightarrow \, ^{1}_{1}P + \, ^{0}_{-1}He$$

The positive charge increases in the process.

(ii) The mass of the particles emitted is negligible.

Consider the following nuclides, which emit beta particles.

(i) $^{14}_{6}C \longrightarrow \, ^{14}_{7}N + \, ^{0}_{-1}e$

(ii) $^{226}_{88}n \longrightarrow \, ^{226}_{89}Ac + \, ^{0}_{-1}e$

The emission of gamma rays which is a form of energy always accompanies other radioactive emissions. They are produced when the remaining particles in the nucleus re-organise themselves into more stable arrangements. Gamma rays are not shown when writing nuclear equations because they have no effect on mass number and atomic number of a nuclide.

For example:

$$^{236}_{92}U \longrightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n + \text{energy}$$

Radioactive Decay Series.

A radioactive decay series represents the sequential and continuous disintegration of unstable nuclide until a stable nuclide is formed. For example starting with thorium–232.

The following series is obtained;

$$^{232}_{90}Th \xrightarrow{\alpha} {}^{228}_{88}Ra \xrightarrow{\beta} {}^{228}_{89}Ac \xrightarrow{\beta} {}^{228}_{90}Th \xrightarrow{\alpha} {}^{224}_{88}Ra \xrightarrow{\alpha} {}^{220}_{86}Rn \xrightarrow{X} {}^{216}_{24}B \xrightarrow{\alpha} {}^{212}_{82}Pb \xrightarrow{\beta} {}^{212}_{83}Bi \xrightarrow{\alpha} {}^{208}_{81}TI \xrightarrow{\beta} {}^{208}_{82}Pb$$

In this decay series, natural decay ends when stable lead-208 is formed. Notice that the $\frac{n}{p}$ ratios of lead –208 is about 1.5:1 which is in the stable region. This decay series is known as the Thorium decay series.

Nuclear Fission

Nuclear fission *is the splitting process a heavy nuclide undergoes when bombarded by a fast-moving neutron*.

The large unstable nuclide absorbs a neutron and immediately splits up into two approximately equal fragments together with a number of smaller particles such as a neutron. During this process, much energy is liberated.

For example:

$$^{236}_{92}U + {}^{1}_{0}n \longrightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n + \text{energy}$$

The mass of the products added together equal the mass of the original nuclide plus the mass of the neutron. The three neutrons produced further bombard more nuclei and more neutrons are formed. This results in a chain reaction.

Energy is liberated due to the fact that the total mass of the products is slightly less than the mass of the initial nuclides. This difference in mass is radiated as energy. A very small loss in mass results in an enormous amount of energy being released.

This energy can be tapped and utilised to generate electrical energy and other forms of energy under controlled conditions. The enormous heat is used to heat water to produce steam which then turns turbines to produce electricity. The energy of an atomic bomb is due to nuclear fission of uranium–235.

Nuclear Fusion

***Nuclear fusion occurs when nuclei combine together when they are made to collide at high velocity resulting in the formation of a heavy nucleus and release of energy*.**

Some sub-atomic particles such neutrons are also released during nuclear fusion. The energy released after fusion causes other nuclide to collide and a chain reaction occurs. For example:

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

+ energy

The sum of mass numbers and atomic numbers of the products equal the sum of mass numbers and atomic number of the reactants.

The energy released during nuclear fusion can be harnessed and converted into other forms of energy such as electrical energy.

The hydrogen bomb works on the principle of nuclear fusion.

Nuclear fission and fusion are similar in that:

1. In both cases a large quantity of energy is released.
2. Both processes results in chain reactions.
3. In both cases sub-atomic particles such as neutrons accompany the process.
4. The energy released can be harnessed and converted into other forms of useful energy such as electrical energy.
5. The large amount of energy produced in both reactions can be very destructive when misused such as in nuclear warfare.

Applications of Radioactivity

Besides production of energy, other uses of radioactivity include the following:

Medical applications

- Used to destroy cancerous tissue when a patient is exposed to correct dose of radiation from radioactive nuclide such as a cobalt–60 and caesium–137, it is possible to destroy cancerous growth without serious damage to other tissues of the patient.
- Sterilisation of surgical instruments using gamma radiation.
- Radioactive iodine (iodine–131) is used in patients with defective thyroid to enable doctors to follow the path of iodine through the body.
- Used to monitor growth in bones and healing of fractures.
- For providing power in heart pace setters.
- Detecting leakages in underground water or oil pipes without digging them out.

Agricultural applications

Radioactivity may be used in monitoring:

- Photosynthesis and related process; Carbon(VI) oxide containing radioactive carbon –14 is used, and the path of this carbon can be followed during the growth of the plant.
- Absorption of phosphate fertilisers; radioactive phosphorus can be used to determine the rate of absorption of the fertiliser.

Other uses

- Preservation of food by exposing micro-organisms to gamma radiation which kills them.
- Gauging the thickness of thin metal and paper sheets.
- Measuring the level of food in canned and packed food.
- Determining the age of archeological materials in fossils from carbon –14 dating.
- Manufacture of nuclear weapons and atomic bombs.

Dangers of Radioactivity

Environmental Pollution

Environmental pollution occurs when radioactive materials emit radiation into the atmosphere. Long term exposure to low dosages of these radiations can cause genetic mutation in living tissue leading to anaemia, bone cancer and other forms of cancer.

Disposal of nuclear waste is of particular concern since some of the radioactive materials have very long half-life.

Testing of nuclear weapons in the oceans also causes environmental pollution since plants and other living organisms may take in the radioactive materials released in the water.

When not put into proper use, radioisotopes can be used as weapons of mass destruction as it happened in the cities of Hiroshima and Nagasaki, Japan during the Second World War.

Control of Environmental Pollution

Environmental pollution can be controlled by proper use, storage and disposal of radioactive materials as well as regular checks of equipment which emit radiations.

Revision Exercise

1. 2006 Q 4

(a) Complete the nuclear equation below. (1 mark)

$$^{37}_{18}A + \dots\dots\dots \longrightarrow ^{37}_{17}B$$

(b) (b) State one:

(i) Use of radioisotopes in agriculture. (1 mark)

(ii) Danger associated with exposure of human beings to radioisotopes. (1 mark)

2. 2007 Q 14 P1

(a) Distinguish between nuclear fission and nuclear fusion. (2 marks)

(b) Describe how solid wastes containing radioactive substances should be disposed of. (1 mark)

3. 2008 Q 24 P1

(a) A radioactive substance emits three different particles. Give the symbol of the particle with the highest mass. (1 mark)

(b) (i) Find the values of **Z_1** and **Z_2** in the nuclear equation below. (1 mark)

$$^{Z1}_{92}U + ^{1}_{0}n \longrightarrow ^{37}_{17}B + ^{140}_{Z2}Xe + 2\,^{1}_{0}n$$

(ii) What type of nuclear reaction is represented in represented in b (i) above? (1 mark)

4. 2009 Q 6d P2

Naturally occurring uranium consist of three isotopes which are radioactive.

Isotope	^{234}**U**	^{235}**U**	^{238}**U**

Abundance 0.01% 0.72% 99.27%

(i) Which of these isotopes has the longest half-life? Give reasons. (1 mark)

(ii) Calculate the relative atomic mass of uranium. (2 marks)

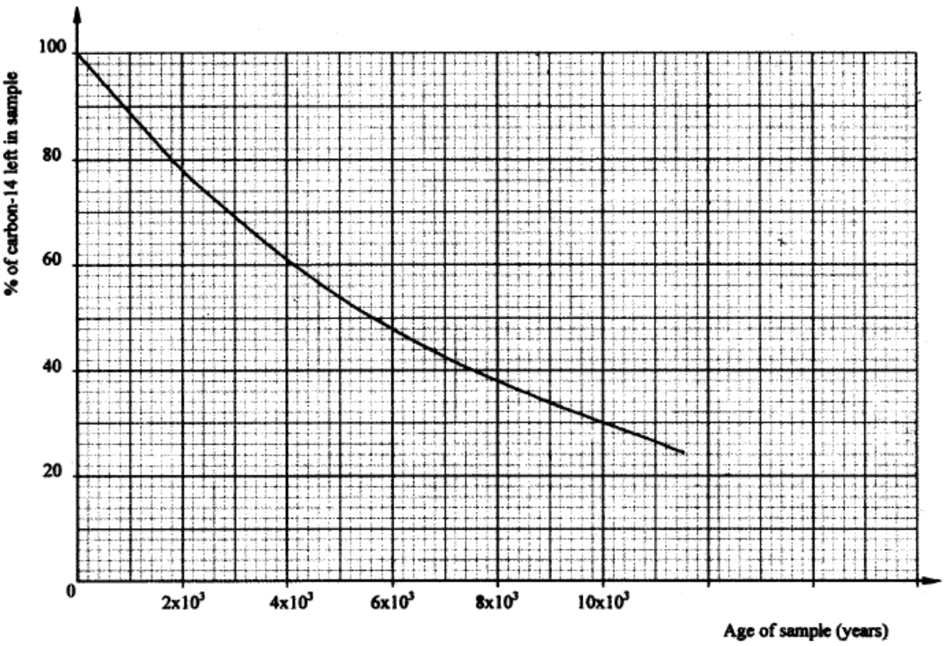
(iii) $^{235}_{92}\mathbf{U}$ is an alpha emitter. If the product of the decay of this nuclide is thorium (Th), Write a nuclear equation for the process. (1 mark)

(iv) State one use of radioactive isotopes in the paper industry. (2 marks)

5. 2010 Q 9 P1

Carbon -14, $^{14}_{6}\mathbf{C}$, is used in carbon dating. It decays to form nitrogen, $^{14}_{7}\mathbf{N}$

The graph below shows the amount of carbon -14 left in a sample against its age in years.



(a) Write a nuclear equation for the decay process of carbon -14. (1 mark)

(b) From the graph, determine the;

(i) Half-life of carbon -14; (1 mark)

(ii) Percentage of carbon -14 in a sample whose age is 1950 years. (1 mark)

6. 2011 Q 2 P1

(a) Complete the nuclear equation below: (1 mark)

$$^{131}_{53}\mathrm{I} \longrightarrow {}^{131}_{54}\mathrm{I} + \_\_\_\_\_\_$$

(b) The half-life of $^{131}_{53}\mathbf{I}$ is 8 days. Determine the mass of $^{131}_{53}\mathbf{I}$ remaining if 50 grams decayed for 40 days. (1 mark)

(c) Give one harmful effect of radioisotopes. (1 mark)

7. 2012 Q9 P1
120g of iodine - 131 has a half-life of 8 days decays for 32 days. On the grid provided, plot a graph of the mass of iodine - 131 against time. (3 marks)

8. 2013 Q8 P1
Draw a labelled diagram to illustrate how alpha, beta and gamma radiations can be distinguished from each other. (3 marks)

9. 2013 Q6 P2
(a) Distinguish between a neutron and proton. (1 mark)

(b) What is meant by a radioactive substance? (1 mark)
(c) State two dangers associated with radioactive substance in the environment. (2 marks)

(d) The two isotopes of hydrogen, deuterium and tritium T react to form element y and neutron particles, according to the equation below;

$$^{2}_{1}\mathbf{D} + {}^{3}_{1}\mathbf{T} \longrightarrow {}^{a}_{b}\mathbf{Y} + {}^{1}_{0}\mathbf{n}$$

(i) What is the atomic:
(I) Mass of Y? (1 mark)
(II) Number of Y? (1 mark)

(ii) What name is given to the type of reaction undergone by the isotopes of hydrogen? (1 mark)

(e) (i) What is meant by half-life of a radioactive substance? (1 mark)
(ii) 288 g of a radioactive substance decayed to 9 g in 40 days. Determine the half-life of the radioactive substance. (2 marks)

10. 2014 Q8 P1
(a) Complete the nuclear reaction below. (1 mark)

$$^{226}_{88}\mathbf{Q} \longrightarrow {}^{222}_{86}\mathbf{P} +$$

(b) State two uses of radioisotopes in health. (2 marks)

11. 2015 Q19 P1
A radioactive substance weighing M kg took 1900 years for the original mass to reduce to 15 kg. Given that the half-life of the radioactive substance is 380 years;
(a) Determine the original mass of the radioactive substance. (2 marks)
(b) State two uses of radioactivity in medicine. (1 mark)

12. 2017 P1 Q2.
Calculate the values of X and Y in the following nuclear equation.
$^{239}_{92}\mathbf{U} \longrightarrow {}^{X}_{Y}\mathbf{Th}$ +2α+2β (2 mark)

13. 2017 P2 Q7.
The decay rates of a sample of a radioisotope of bismuth at different time intervals is indicated in the following table.

Time (hours)	0	5	10	15	20	25
Rate of disintegration in counts s^{-1}	730	570	455	365	292	232

(a)
(i) Draw a graph of disintegration rate against time. (3 marks)
(ii) Determine the half-life of bismuth. (1 mark)
(iii) What would be the effect on the curve if half the amount of sample of bismuth were used. (1 mark)

(b) Radioactivity has several applications. State one application of radioactivity in:
(i) Medicine (1 mark)
(ii) Agriculture (1 mark)
(iii) Tracers (1 mark)
(iv) Nuclear power station (1 mark)

(c) State two dangers associated with radioactivity. (2 marks)

14. 2018 P1 Q 19.
(a) Give the symbols of the two charged particles emitted by a radioactive isotope. (2 marks)
(b) An isotope $^{210}_{82}\mathbf{Pb}$ disintegrates by emitting two beta particles. Determine the mass number and atomic number of the resulting nuclide. (1 mark)

15. 2019 P1 Q 22.
The diagram in **figure 6** shows radiations emitted by a radioactive sample.

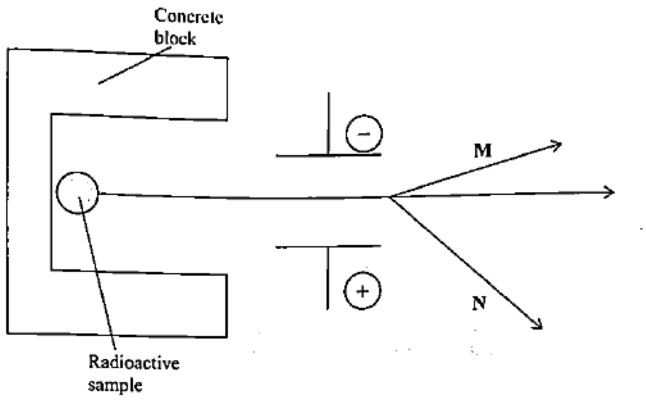


Figure 6

(a) Identify radiations:

(i) M .... (1 mark)

(ii) N .... (1 mark)

(b) Explain what would happen when a sheet of paper is placed in the path of the two radiations. (1 mark)