New

# NATIONAL 5

# PHYSICS



# "Nuclear Radiation"

Spread 1

# The Structure of Atoms

**Key Learning Objectives** **To find out:**

- the name, relative mass, position and electric charge of the three particles atoms are made up of
- why atoms are electrically neutral
- why the nucleus of some atoms is unstable
- the process an unstable atomic nucleus goes through in order to become stable
- the meaning of the term 'nuclear radiation'
- the name and nature of the three main types of 'nuclear radiation'

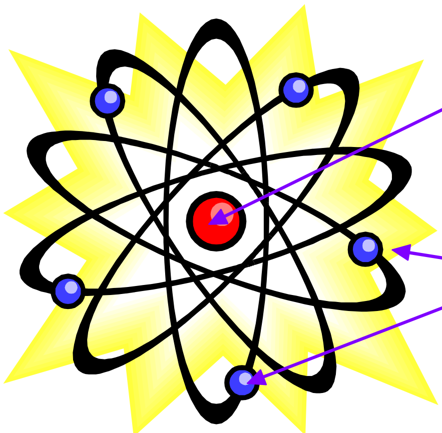
*In order to tackle the Physics in this 'Nuclear Radiation unit', we must first be able to understand the structure of atoms - the tiny building blocks that make up all materials.*

## 1) The Structure of Atoms

An atom contains particles called neutrons and protons that are tightly-packed together in its centre, called the nucleus.
Neutrons and protons have the same mass.

Circling around the nucleus are much smaller particles called electrons.
Electrons have almost zero mass.

The structure of a typical atom is represented by the diagram below:




**NOT TO SCALE**

There are two types of electric charge: positive (+) and negative (-). These are exact opposites.

Neutrons do not have an electric charge.

Protons have a positive (+) electric charge.

Electrons have a negative (-) electric charge.

Atoms contain equal numbers of positively charged protons and negatively charged electrons, so the electric charges cancel out. Atoms therefore have no overall electric charge - atoms are said to be electrically neutral.

The table below summarises the properties of neutrons, protons and electrons:

| Particle | Position in Atom | Relative Mass | Electric Charge |
|---|---|---|---|
| neutron | nucleus (centre) | 1 | 0 |
| proton | nucleus (centre) | 1 | +1 |
| electron | circling the nucleus | almost zero | -1 |

## 2) Nuclear Radiation

The nucleus of some atoms is unstable because it contains the wrong ratio of neutrons to protons.

To become 'more stable', the nucleus can emit (give out) an energy-carrying particle. When this happens, the nucleus of a different atom is formed - this contains a different number of neutrons and a different number of protons to the original nucleus.

From this newly-formed nucleus, an energy-carrying wave may then be emitted. This does not change the structure of the newly-formed nucleus - this nucleus still contains the same number of neutrons and the same number of protons.

The energy-carrying particle and wave are referred to as nuclear radiation.

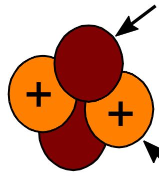
**Nuclear radiation is a particle or wave emitted from the unstable nucleus of an atom.**

The three main types of nuclear radiation are:

- **alpha particles [symbol α]**

  These are relatively slow-moving, positively-charged particles, emitted from the nucleus of an atom at up to 10% of the speed of light in air. (Their speed depends on the type of nucleus).

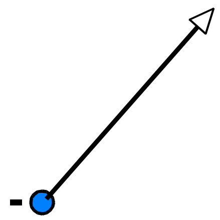
  They consist of two protons and two neutrons joined together, just like the nucleus of a helium atom. They are the largest type of nuclear radiation, with the greatest mass.




- **beta particles [symbol β]**

  These are electrons - very tiny, negatively-charged particles with almost zero mass.

  They are created when a neutron in the nucleus of an atom splits up into a proton (that stays in the nucleus) and the electron (beta particle) that is emitted from the nucleus at a continuous range of speeds, up to 90% of the speed of light in air. (Their maximum speed depends on the type of nucleus).



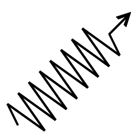

diagrams copyright M. Cunningham

- **gamma rays [symbol γ]**

  These are not particles.

  They are transverse electromagnetic waves - the 'highest energy' member of the electromagnetic spectrum. They have no mass and no electric charge. They travel through air at the same speed as light: $3.0 \times 10^{8}$ m $s^{-1}$.

  They may be emitted as a 'short burst' from the nucleus of the atom that has just been formed by the emission of an alpha or beta particle from a different nucleus. This happens if the newly-formed nucleus still has too much energy to be stable. The nucleus releases this extra energy by emitting a gamma ray.




This table summarises some information about alpha particles, beta particles and gamma rays:

| Type of Nuclear Radiation | Symbol | Nature | Relative Mass | Electric Charge | Speed in Air |
|---|---|---|---|---|---|
| alpha particle | α | 2 protons + 2 neutrons joined together. Identical to the nucleus of a helium atom. | 4 | +2 | up to 10% of speed of light |
| beta particle | β | fast-moving electron | almost zero | -1 | up to 90% of speed of light |
| gamma ray | γ | high energy, transverse electromagnetic wave | 0 | 0 | speed of light |

# Spread 2 Relative Penetration of Nuclear Radiation

**Key Learning Objectives** **To find out:**

- the relative ability of alpha particles, beta particles and gamma rays to penetrate [pass through] materials
- the meaning of the terms 'ionisation' and 'ionising radiation'
- the effect of 'ionisation' by nuclear radiation on an electrically-neutral atom
- the relative ionising effect of alpha particles, beta particles and gamma rays

## 1) Relative Penetration of Nuclear Radiation

Nuclear radiations can travel different distances through different materials.

When alpha particles, beta particles and gamma rays pass through a material, they collide with the atoms or molecules in that material, transferring their energy to the material. Once all the energy from the alpha particle, beta particle or gamma ray has been transferred to a material, they cannot travel any further through it - we say they have been absorbed by the material.

- **alpha particles [symbol α]**

  Because alpha particles have by far the largest size and mass of all the types of nuclear radiation, it is difficult for them to pass through a material without colliding with many of the atoms/molecules in it. As a result, the alpha particles lose their energy 'quickly' to the material - so they can only travel a short distance through it before being absorbed.

  For example, alpha particles can only travel a few centimetres through air before being absorbed and are absorbed by a thin sheet of paper.

- **beta particles [symbol β]**

  Because of their relatively small size and mass compared to alpha particles, beta particles collide less often with any atoms/molecules in the material they are travelling through. As a result, beta particles lose their energy 'less quickly' to the material - so can travel a greater distance through it before being absorbed.

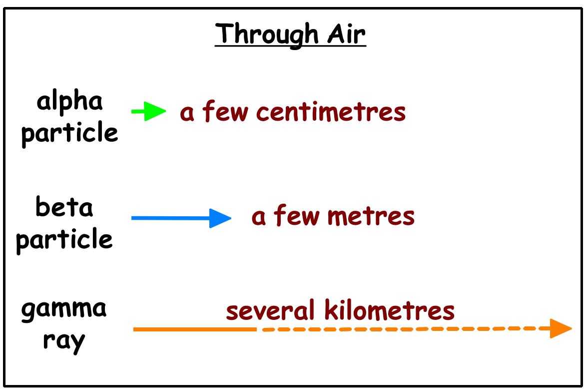
  For example, beta particles can travel a few metres through air before being absorbed. They can pass through paper but are absorbed by approximately 3 millimetres of aluminium.

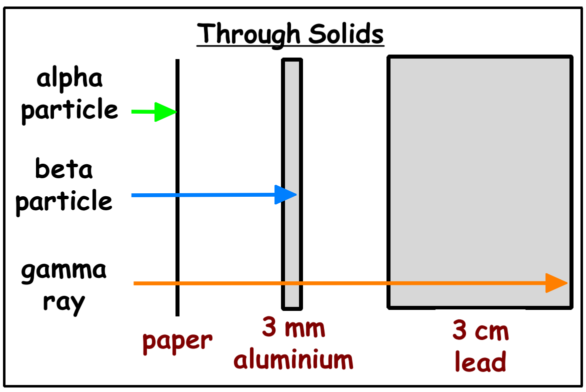
- **gamma rays [symbol γ]**

  Because they are not particles, but a high-energy wave, gamma rays can travel much further through a material than alpha and beta particles before they are absorbed by the material.

  For example, gamma rays can travel through several kilometres of air before being absorbed. They can pass through paper and 3 millimetres of aluminium, but are absorbed by approximately 3 centimetres of lead.

The diagrams below summarise the relative penetrating ability of alpha particles, beta particles and gamma rays:



## 2) Ionisation of Atoms by Nuclear (Ionising) Radiation

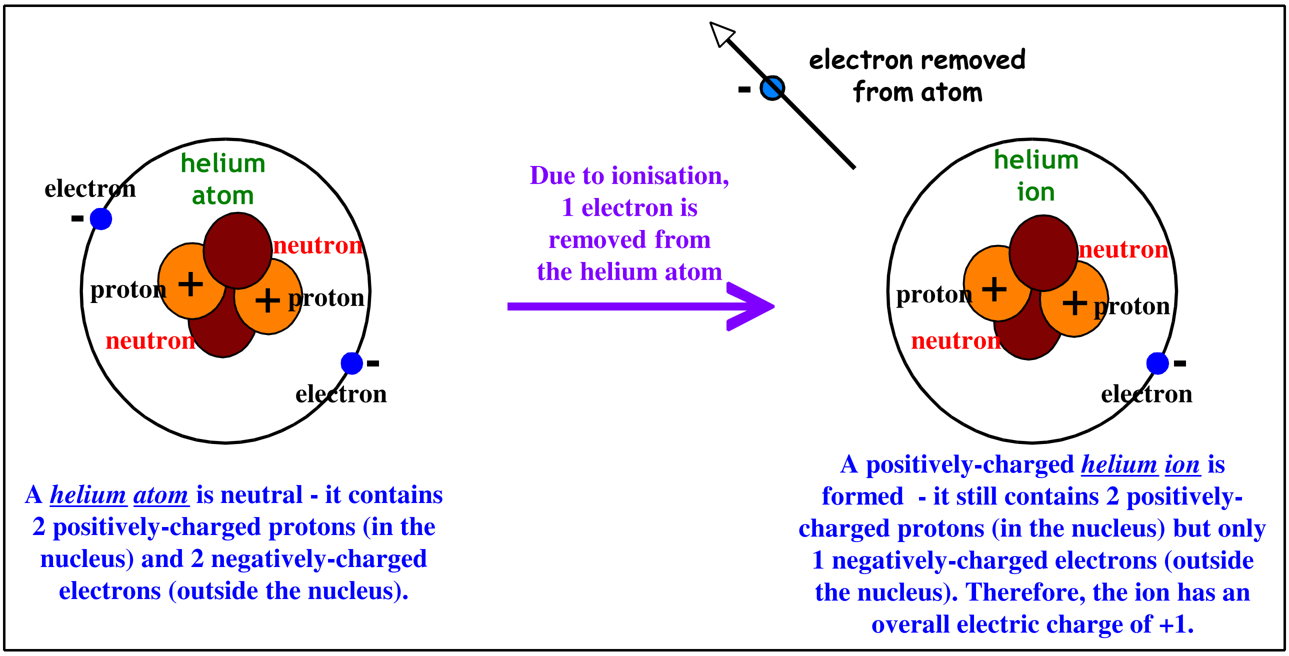
When nuclear radiation (an alpha particle, beta particle or gamma ray) is passing through a material, it can remove one or more electrons from the electrically-neutral atoms that make up the material. This is known as 'ionisation' - so nuclear radiation is described as 'ionising radiation'.

**Ionisation is the removal of one or more electrons from an atom (by nuclear radiation).**

**Ionising radiation is radiation that can remove one or more electrons from an atom.**

**Any electron removed from an atom during ionisation is NOT a beta particle - the electron comes from outside the nucleus.**

The diagram below represents the ionisation of a helium atom:






Alpha particles cause far more ionisation than beta particles or gamma rays.

This is because, of these three types of nuclear radiation, alpha particles have by far the largest size, mass and electric charge - this makes it easier for them to remove one or more electrons from an atom.

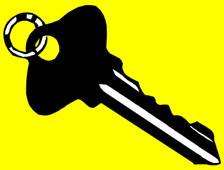
Because beta particles have mass (although almost zero) and an electric charge, they cause more ionisation than gamma rays which are electromagnetic waves with no mass and no electric charge.

This table summarises the ionising ability of alpha particles, beta particles and gamma rays:

| Type of Nuclear Radiation | Ionising Ability |
|---|---|
| alpha particle | high |
| beta particle | low |
| gamma ray | very low |

# Radioactive Decay and Activity

**Key Learning Objectives** **To find out:**



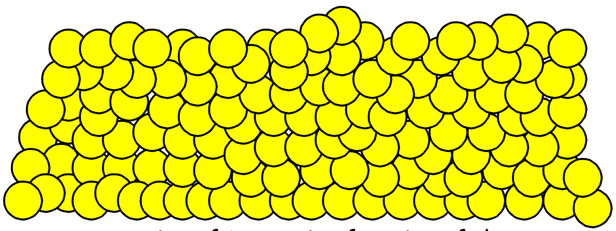
- what happens during the process of 'radioactive decay'
- the meaning of the term 'activity' as applied to a radioactive source in terms of the 'number of nuclear decays' and the 'time'
- the unit for 'activity'
- that 1 becquerel (Bq) is equivalent to 1 atomic nucleus decaying per second
- how to carry out calculations involving 'activity', 'number of nuclear disintegrations' and 'time'
- the meaning of the term 'background radiation'
- the sources of 'background radiation'

## 1) Radioactive Sources and Radioactive Decay

A material that emits (gives out) nuclear radiation [alpha particles, beta particles or gamma rays] is known as a 'radioactive source' - it is said to be 'radioactive'.

A typical radioactive material will be made up of many millions of atoms, most of which will have an unstable nucleus that will try to become more stable by emitting an alpha particle, beta particle or gamma ray. When this happens, the nucleus is said to 'disintegrate' or undergo 'radioactive decay'.





representation of just a tiny fraction of the atoms present in a radioactive material

Radioactive decay is a random process - we cannot predict the exact time at which a particular atomic nucleus present in a radioactive material will disintegrate (decay).

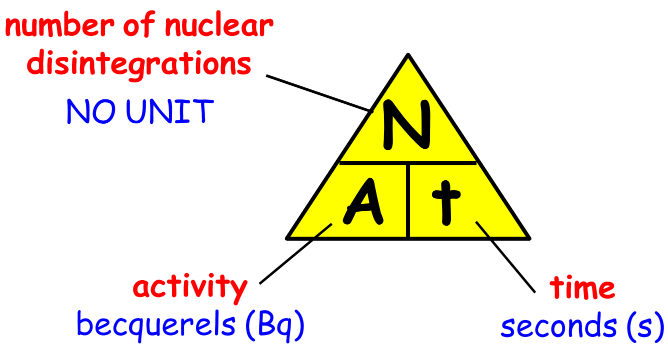
## 2) Activity of a Radioactive Material

**The activity of a radioactive material is the number of atomic nuclei present in the material that disintegrate in one second.**

Activity is measured in becquerels (Bq).

[1 Bq = 1 atomic nucleus disintegrating per second]

$$\text{activity (A)} = \frac{\text{number of nuclear disintegrations (N)}}{\text{time (t)}}$$




$$A = \frac{N}{t}$$

$$N = A\,t$$

$$t = \frac{N}{A}$$

## "Activity" Problems With Solutions

In a radioactive material, 20 000 atomic nuclei disintegrate (decay) in a time of 25 s.

Calculate the **activity** of the radioactive material.

**SOLUTION**

$$A = \frac{N}{t} = \frac{20\,000}{25} = \underline{800\ \text{Bq}}$$

A radioactive material has an activity of 120 Bq.

Calculate the **number** of atomic nuclei present in the material that will disintegrate (decay) in a time of 15 s.

**SOLUTION**

$$N = A\,t = 120 \times 15 = \underline{1\,800\ \text{atomic nuclei}}$$

In a radioactive material of activity 1 500 Bq, 30 000 atomic nuclei disintegrate (decay).

Calculate the **time** this takes.

**SOLUTION**

$$t = \frac{N}{A} = \frac{30\,000}{1\,500} = \underline{15\ \text{s}}$$

## 3) Background Radiation in the U.K.

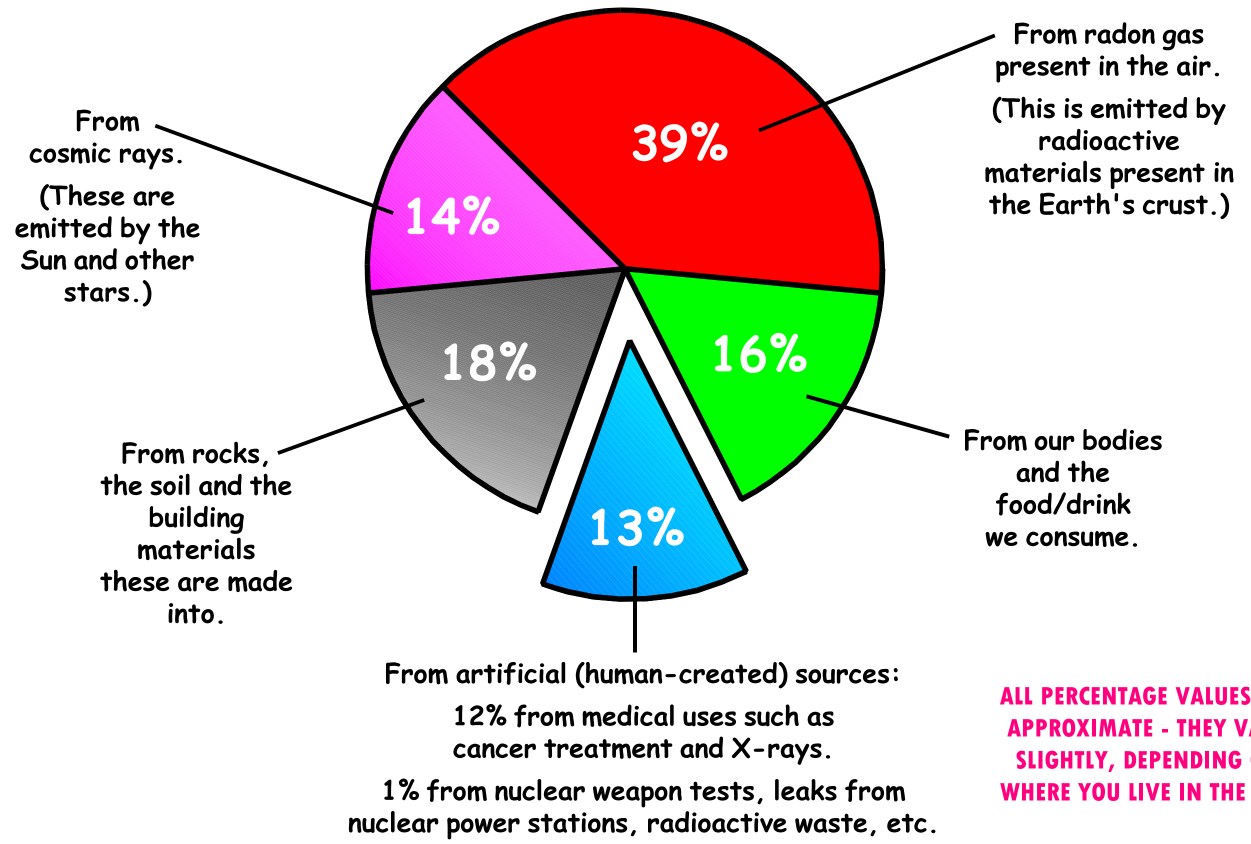
The air around us is slightly radioactive - nuclear radiation (alpha particles, beta particles and gamma rays), and other forms of radiation, are always present in our surroundings (the background).

**Background radiation is radiation from natural and artificial sources that is always present in our surroundings.**

We are exposed to this background radiation 24 hours a day. However, the total dose we receive each year is not high enough to harm us.

The percentage proportions of background radiation we receive each year in the U.K. due to different sources (in terms of a quantity called 'equivalent dose rate') are compared in the pie chart below.

These radiation sources are mainly natural (approximately 87%). Only about 13% of the total background radiation we receive each year is due to artificial (human-created) sources.

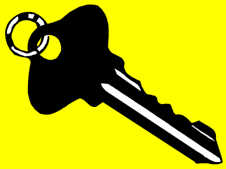



ALL PERCENTAGE VALUES ARE APPROXIMATE - THEY VARY SLIGHTLY, DEPENDING ON WHERE YOU LIVE IN THE U.K.

Spread 4

# Half Life of Radioactive Materials ..........

**Key Learning Objectives** **To find out:**



- that the 'activity' of a radioactive material decreases with time
- the definition of the term 'half-life'
- that the 'half-life' value for any specific radioactive material is always constant
- that different radioactive materials have different 'half-life' values and can be identified by their 'half-life' value
- how to use an 'activity against time graph' to determine the 'half-life' of a radioactive material

## 1) Decrease in the Activity of a Radioactive Material

The 'activity' of a radioactive material decreases with time.

This is because, as time passes, unstable atomic nuclei present in the radioactive material disintegrate (decay), so the number of unstable atomic nuclei present in the radioactive material decreases.

## 2) Half-Life of a Radioactive Material

The term 'half-life' is used to describe the time it takes for half of the unstable nuclei of the atoms present in a radioactive material to disintegrate (decay).
When this happens, the 'activity' of the radioactive material falls to half of its original value.

This leads to two definitions for 'half-life':

**The half-life of a radioactive material is the time it takes for half of the unstable nuclei present in the material to disintegrate (decay).**

OR

**The half-life of a radioactive material is the time it takes for the activity of the material to halve in value.**

The 'half-life' value for any specific radioactive material is always constant.

Different radioactive materials have different 'half-life' values.
The table below shows some of these values:

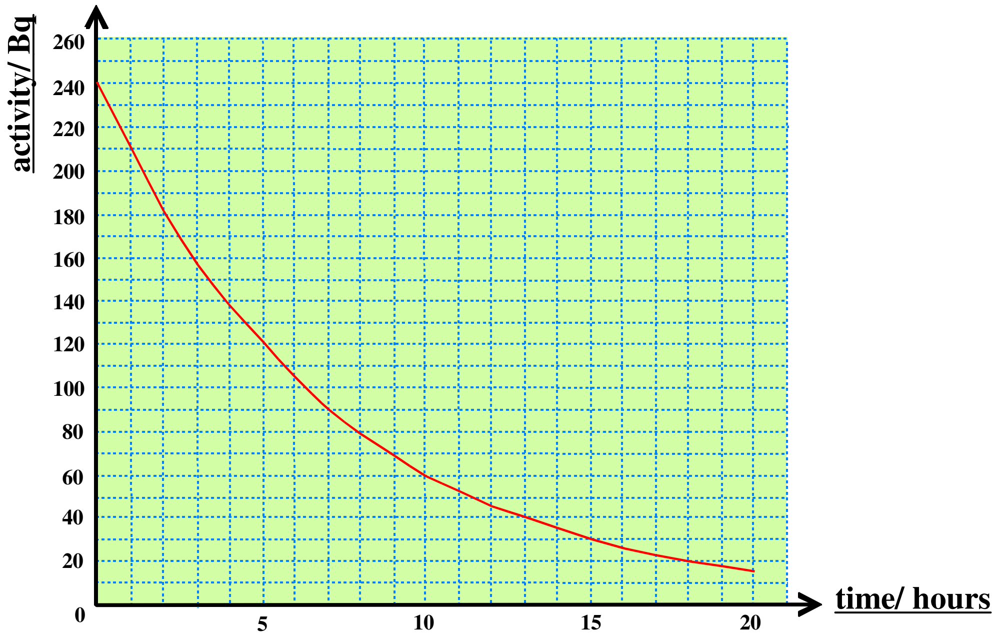
| Radioactive Material | Half-Life |
|---|---|
| radon-220 | 54 seconds |
| copper-66 | 5.2 minutes |
| sodium-24 | 15 hours |
| radon-222 | 3.8 days |
| iodine-131 | 8.1 days |
| cobalt-60 | 5.3 years |
| strontium-90 | 28 years |
| carbon-14 | 5 760 years |
| uranium-235 | 713 000 000 years |
| thorium-232 | 13 900 000 000 years |

A radioactive material can be identified by its 'half-life' value.

## 3) Determining 'Half-Life' From an Activity-Time Graph

For any radioactive material, the line-graph of the material's "activity against the time elapsed" always takes the form shown below. *Notice that the activity decreases with time.*

The numerical values on the axes will be different for different radioactive materials.



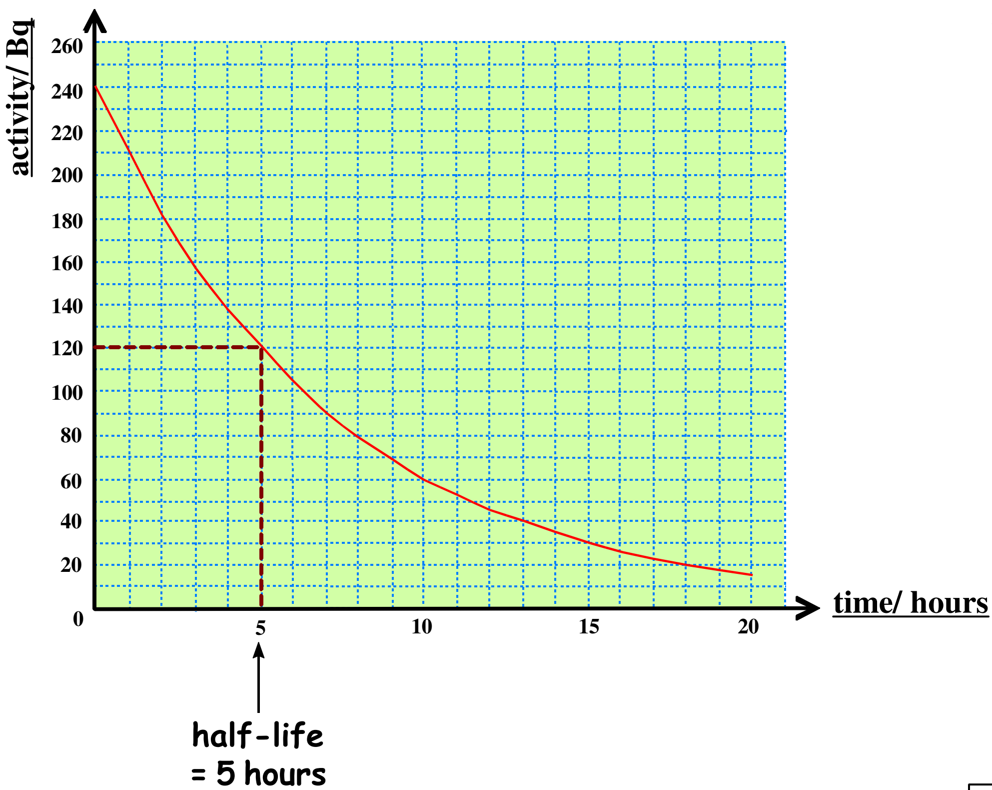

We can use the "activity against time elapsed" graph for a radioactive material to determine the value for the 'half-life' of the material, as shown below:

1) Select the activity value from the graph where the curve cuts the y-axis [in this case, 240 Bq].

2) Halve the selected activity value (divide it by 2) [240 Bq / 2 = 120 Bq].

3) Go to this 'halved activity value' on the y-axis, then draw a horizontal line along from the y-axis to the curve.

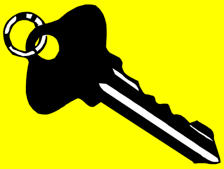
4) Where the horizontal line you have drawn touches the curve, draw a vertical line down from the curve to the x-axis (time) - the point where this line touches the x-axis gives the 'half-life' value for the radioactive material [in this case, 5 hours].



**Spread 5**

# Nuclear Radiation - Detection/Count Rate

**Key Learning Objectives** **To find out:**

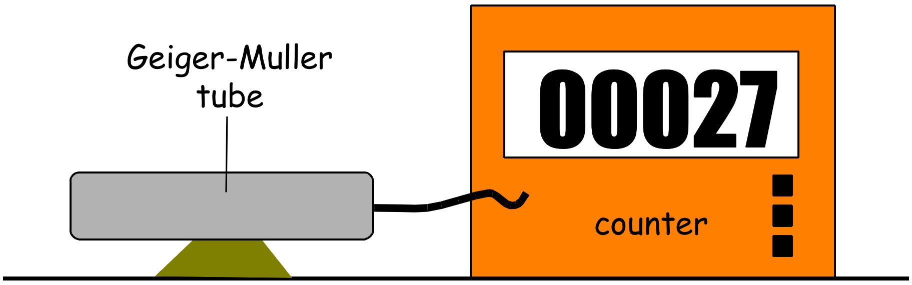


- how we detect nuclear radiation
- how we use a Geiger-Muller tube and counter to determine a 'count rate' value
- that the 'count rate' value of a radioactive material is much less than the 'activity' value of the material, but is proportional to it - so can be used to determine the 'half-life' of the material
- how to carry out an experiment to determine the 'half-life' of a radioactive material using 'count rate' data corrected for the 'count rate' due to background radiation

## 1) Detecting Nuclear Radiation

We detect nuclear radiation using a Geiger-Muller tube connected to a counter.

Every time an alpha particle, beta particle or gamma ray enters the Geiger-Muller tube, the reading on the counter increases by one (and we hear a "click" from the counter).




## 2) Measuring Count Rate

The reading on the counter over a measured time is used to determine a **count rate** value (often in 'counts per minute'). For materials with a very high activity, the count rate value may be measured in 'counts per second').

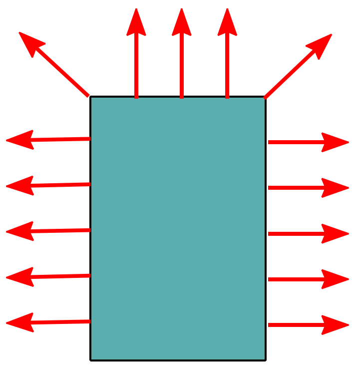
$$\text{count rate} = \frac{\text{counter reading}}{\text{measured time}}$$

count rate: (typically) counts per minute; counter reading: counts; measured time: (typically) minutes

If a radioactive material is placed in front of a Geiger-Muller tube, the count rate value obtained is not the same as the activity of the radioactive material. This is because a radioactive material emits nuclear radiation in all directions and the Geiger-Muller tube can only detect a small fraction of this emitted radiation. Also, some background radiation enters the Geiger-Muller tube and is detected.

The count rate value determined for a radioactive material (adjusted for background radiation) is always far less than the activity value of the radioactive material.

However, the count rate value (adjusted for background radiation) is proportional to the activity value of the radioactive material, so can be used to determine a value for the half-life of the material.



radioactive material (emitting nuclear radiation in all directions)

# Experimental Procedure to Measure Half-Life

## 3) Determining 'Half-Life' From Count Rate Data (Taking Into Account Background Count Rate)

When using count rate values to determine the half-life of a radioactive material, the count rate due to background radiation has to be measured and taken into account because the Geiger-Muller tube detects both the background radiation and part of the radiation emitted by the radioactive material.

### PROCEDURE

#### *1) Determine a value for the "background count-rate"*

**WITH NO RADIOACTIVE MATERIAL PRESENT**

1) The counter is set to zero.

2) The Geiger-Muller tube is switched on for a short set time, often 1 minute (measured with a stopwatch).

3) The counter is stopped after this short set time, then the counter reading is recorded.

4) The "background count-rate" is calculated using the formula shown on the left hand page.

5) Steps 1 - 4 are repeated several times, then an average value is calculated for the "background count rate".

#### *2) Determine several values for the "combined count-rate" (from the background radiation and the radioactive material) at regular time intervals over a long time period*

**WITH A RADIOACTIVE MATERIAL PRESENT A CONSTANT DISTANCE IN FRONT OF THE GEIGER-MULLER TUBE**

At regular time intervals (say every 10 minutes), repeat steps 1-3 above, then calculate the "combined count-rate" for each case, using the formula shown on the left hand page.

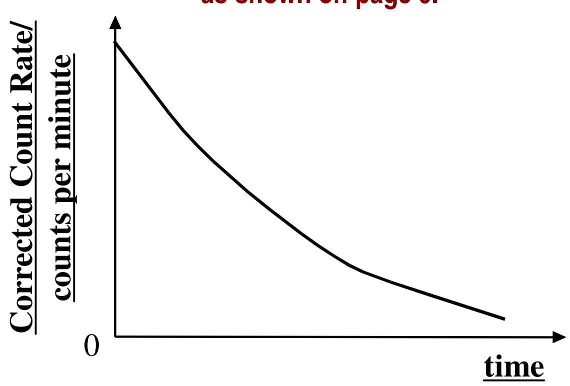
#### *3) Calculate "corrected count-rate" values*

Calculate "corrected count-rate" values (values due to the activity of the radioactive material alone without the effect of background radiation):

**corrected count-rate = combined count rate - average background count rate**

#### *4) Plot a "corrected count-rate against time" graph*

Use this graph to determine the half-life of the radioactive material, as shown on page 9.



# Determining Half-Life - Numerical Data

**Key Learning Objectives** **To find out:**

- how to determine the 'half-life' of a radioactive material using numerical data involving two 'activity' values and the 'time elapsed' between them
- how to determine the 'time taken' for the activity of a radioactive material to fall from one 'activity' value to another using numerical data involving the two 'activity' values and the 'half-life' of the radioactive material
- the dangers of ionising radiation to living cells
- the importance of measuring the dose of ionising radiation human beings are exposed to

## 1) Numerical Data and Half-Life

As well as using an 'activity against time elapsed' graph (or a 'corrected count rate against time elapsed' graph) to determine the half-life of a radioactive material, we can do so by carrying out a calculation using numerical data provided by experiment.

### "Half-Life" Problem 1 With Solution

Determine the half-life of a radioactive material if its activity falls from 400 Bq to 50 Bq in a time of 6 hours.

**SOLUTION**

REMEMBER - after every half-life, the activity halves its value

400 Bq —half-life→ 200 Bq —half-life→ 100 Bq —half-life→ 50 Bq

3 half-lives in 6 hours

$$\therefore \text{half-life} = \frac{6 \text{ hours}}{3} = \underline{2 \text{ hours}}$$

**NOTE 1**
The same question could state that the activity falls from its original value to 1/8 of this value.

In this case, the top line of the solution should be set out as shown below. The rest of the solution working will be identical.

1 —half-life→ 1/2 —half-life→ 1/4 —half-life→ 1/8

**NOTE 2**
Alternatively, the same question could state that the activity falls from its original value to 12.5% of this value.

In this case, the top line of the solution should be set out as shown below. The rest of the solution working will be identical.

100% —half-life→ 50% —half-life→ 25% —half-life→ 12.5%

Conversely, if we are given the half-life of a radioactive source, we can calculate the time taken for its activity to fall from one stated value to another.

### "Half-Life Problem 2 With Solution

The half-life of a radioactive material is 3 hours.

Determine the time it will take for the activity of the material to fall from 600 Bq to 150 Bq.

**SOLUTION**

REMEMBER - after every half-life, the activity halves its value

600 Bq —half-life→ 300 Bq —half-life→ 150 Bq

2 half-lives occur

$\therefore$ time taken = 2 x 3 hours = <u>6 hours</u>

# Ionising Radiation and its Danger to Living Cells

*"Ionising radiation" was covered on page 5 of this booklet.*
*Before studying the material below, you should re-read page 5.*

**Ionising radiation is radiation that can remove one or more electrons from an atom.**
**The atom then becomes a positively-charged ion.**

## 2) The Dangers of Ionising Radiation to Living Cells

Ionising radiation can be very dangerous to the human body.

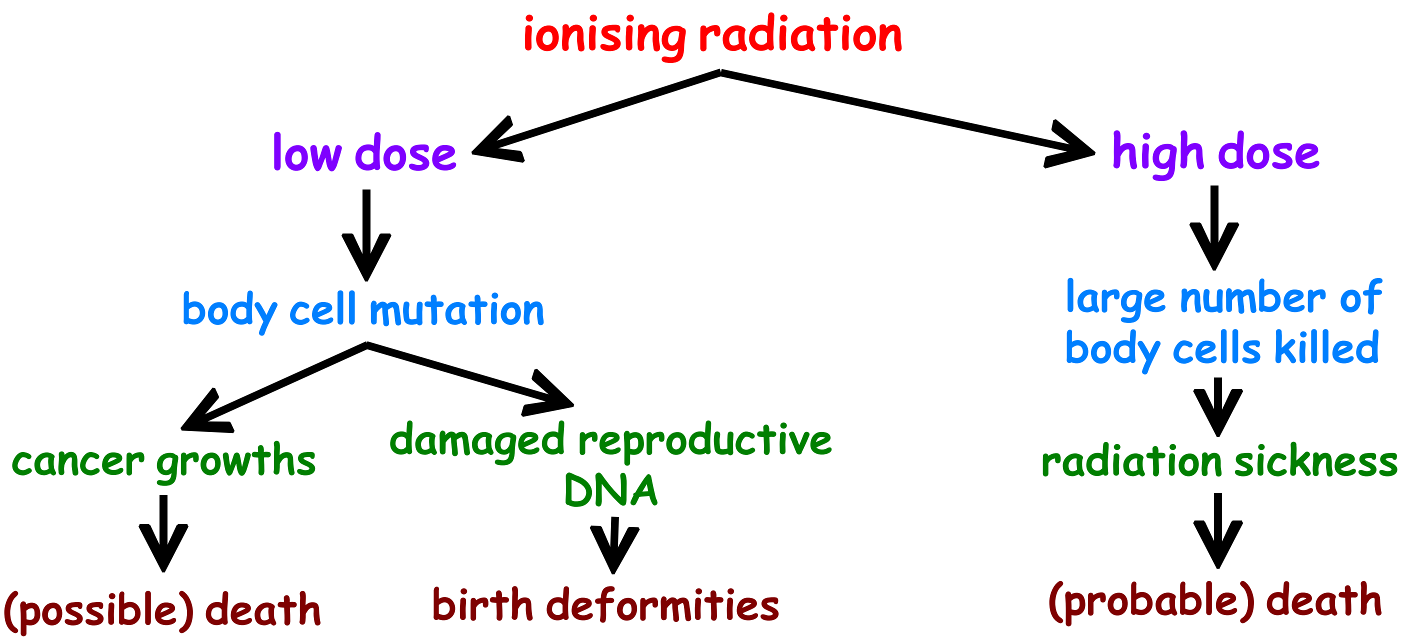
Through ionisation, low doses of radiation can damage DNA molecules present in the nucleus of human body cells. DNA molecules control the way in which body cells behave, so damaged cell DNA can make body cells behave differently from normal - this is known as 'mutation'.

- mutated body cells can divide uncontrollably, forming cancer growths - these may lead to death
- damaged 'reproductive DNA' can cause 'birth deformities' in the next and future generations of children

Through ionisation, high doses of radiation can quickly kill large numbers of human body cells by damaging vital enzyme molecules present in the cells.

- the function of vital body organs may be affected - this is known as radiation sickness, which usually results in death.

This information is summarised below:

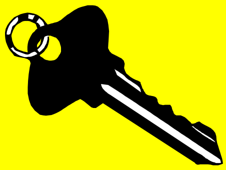



For these reasons, it is important to measure the dose of ionising radiation human beings are exposed to - this is an important 'health issue'.

*The next 4 double-page spreads deal with the doses of ionising radiation human beings are exposed to.*

# Spread 7 Radiation Doses - Absorbed Dose ..........

**Key Learning Objectives** **To find out:**



- what happens to the energy of 'ionising radiation' that strikes the human body
- the meaning of the term 'absorbed dose' and the unit it is measured in
- that 1 gray (Gy) is equivalent to 1 J of energy absorbed by 1 kg of body tissue, i.e., 1 Gy = 1 J $kg^{-1}$
- how to solve problems involving 'absorbed dose', 'energy absorbed' and 'mass of absorbing body tissue'
- that some types of 'ionising radiation' are more harmful to the human body than other types
- that a number known as the 'weighting factor' is used to compare the harm that equal absorbed doses of radiation do to the same sample of human body tissue

## 1) Radiation Doses

When ionising radiation (alpha, beta, gamma or other types) strikes the human body, the energy of the radiation is absorbed by the body tissue - we say that "the body tissue absorbs a dose of radiation".

## 2) Absorbed Dose

**When ionising radiation strikes the human body and is absorbed, the absorbed dose is the quantity of energy from the radiation absorbed per kilogram of body tissue.**

Absorbed dose is measured in grays (Gy).

[1 Gy = 1 J of energy absorbed by 1 kg of body tissue = 1 J $kg^{-1}$]

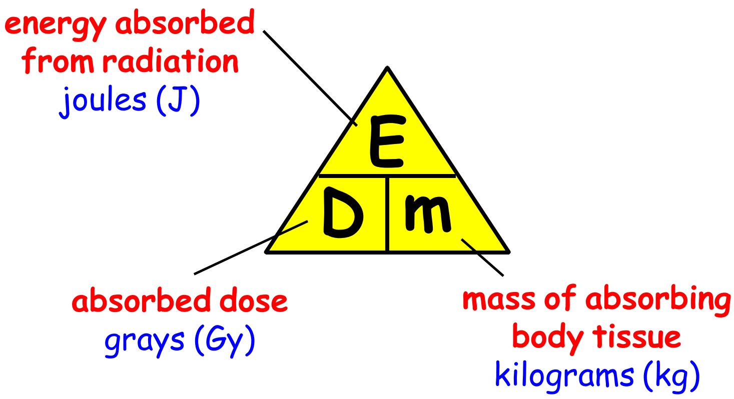
**NOTE**

1 gray (Gy) is a very large quantity.

Typical absorbed dose values are measured in micro-grays (µGy) or milli-grays (mGy).

1 µGy = 0.00000 1 Gy = $(1 \times 10^{-6})$ Gy     1 mGy = 0.001 Gy = $(1 \times 10^{-3})$ Gy

$$\text{absorbed dose (D)} = \frac{\text{energy absorbed from radiation (E)}}{\text{mass of absorbing body tissue (m)}}$$




$$D = \frac{E}{m}$$

$$E = D\,m$$

$$m = \frac{E}{D}$$

## "Absorbed Dose" Problems With Solutions

A 0.015 kg sample of liver tissue absorbs $3.7 \times 10^{-8}$ J of energy when exposed to ionising radiation.

Calculate the absorbed dose for the liver tissue.

**SOLUTION**

$$D = \frac{E}{m}$$

$$= \frac{3.7 \times 10^{-8}}{0.015}$$

$$= \underline{\underline{2.5 \times 10^{-6}\ Gy}}$$

(or $\underline{\underline{2.5\ \mu Gy}}$)

When exposed to ionising radiation, a 0.018 kg sample of lung tissue receives an absorbed dose of 3.5 μGy ($3.5 \times 10^{-6}$ Gy).

Calculate the energy the lung tissue absorbs from the radiation.

**SOLUTION**

$$E = D\,m$$

$$= (3.5 \times 10^{-6}) \times 0.018$$

$$= \underline{\underline{6.3 \times 10^{-8}\ J}}$$

A sample of heart tissue, when exposed to ionising radiation, receives an absorbed dose of 4.0 mGy ($4.0 \times 10^{-3}$ Gy) as it absorbs $1.8 \times 10^{-4}$ J of energy.

Calculate the mass of the heart tissue.

**SOLUTION**

$$m = \frac{E}{D}$$

$$= \frac{1.8 \times 10^{-4}}{4.0 \times 10^{-3}}$$

$$= \underline{\underline{0.045\ kg}}$$

# 3) 'Weighting Factor' for Ionising Radiation

When ionising radiation is absorbed by human body tissue, the tissue may be damaged.

The amount of damage caused to the tissue depends on the type of ionising radiation absorbed - this is because different types of radiation cause a different amount of ionisation to the atoms in human body cells as the radiation passes through the body and is absorbed.

To compare the amount of damage different types of ionising radiation cause to the same sample of human body tissue, each type of ionising radiation is assigned a number, known as a weighting factor. For the same sample of human body tissue exposed to ionising radiation, the higher the weighting factor of the radiation, the greater the damage done to the tissue.

The weighting factor for different types of ionising radiation is shown in the table below:

| Type of Ionising Radiation | Weighting Factor ($w_r$) |
|---|---|
| alpha particles | 20 |
| beta particles | 1 |
| gamma rays | 1 |
| X-rays | 1 |
| slow neutrons | 2.3 |
| fast neutrons | 10 |

NOTE

X-rays (like gamma rays) are high-energy electromagnetic waves. However, they are not emitted from the nucleus of an atom, so are not 'nuclear radiation'.

Slow neutrons and fast neutrons are 'nuclear radiation' - they are emitted from the nucleus of an atom. They take part in a process called 'nuclear fission' (see pages 24-25).

Weighting factor ($w_r$) does not have a unit - it is not a physical quantity, just a number used to compare the damage different types of radiation will cause to the same sample of human body tissue.

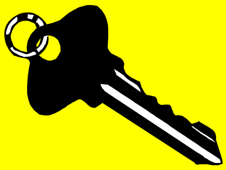
Looking at the weighting factor values in the table, it can be seen that:

- if a sample of human body tissue receives the same absorbed dose of alpha particles and beta particles, the alpha particles will cause 20 times more damage than the beta particles to the tissue sample
- if a sample of human body tissue receives the same absorbed dose of alpha particles and fast neutrons, the alpha particles will cause 2 times more damage than the fast neutrons to the tissue sample.

**Spread 8**

# Radiation Doses - Equivalent Dose ........

**Key Learning Objectives**



**To find out:**

- the meaning of the term 'equivalent dose' and the unit it is measured in
- that 1 Sv = 1 J $kg^{-1}$ (the same unit as 'absorbed dose')
- how to solve problems involving 'equivalent dose', 'absorbed dose' and 'weighting factor' for the absorbed ionising radiation

## Equivalent Dose

It is important to be able to identify and compare the biological harm different types of ionising radiation can do to the same sample of human body tissue.

We need to take into account both the energy of the ionising radiation striking the body tissue and the type of ionising radiation.

To achieve this, we multiply the 'absorbed dose' of ionising radiation the body tissue receives by the 'weighting factor' for the radiation - this gives a quantity known as the 'equivalent dose' (H).

**Equivalent dose is a quantity used to identify and compare the biological harm different types of ionising radiation can do to the same sample of human body tissue, taking into account both the energy of the radiation striking the body tissue and the type of radiation.**

Equivalent dose is measured in sieverts (Sv).

[1 Sv = 1 J $kg^{-1}$ - the same unit as 'absorbed dose']

For the same sample of human body tissue exposed to ionising radiation, the higher the equivalent dose of radiation it receives, the greater the biological harm it will be subjected to.

**NOTE**

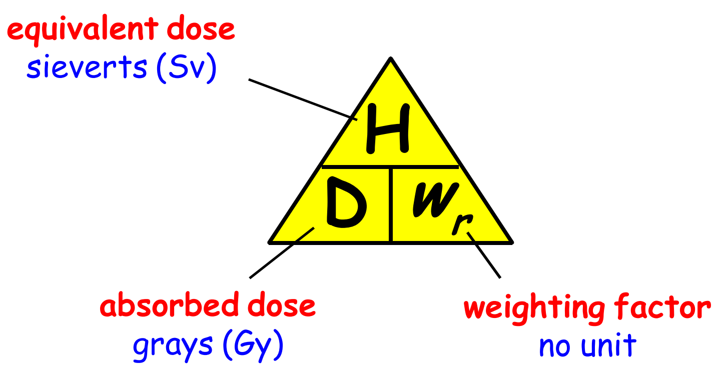
1 sievert (Sv) is a very large quantity.

Typical equivalent dose values are measured in micro-sieverts (μSv) or milli-sieverts (mSv).

1 μSv = 0.00000 1 Sv = $(1 \times 10^{-6})$ Sv

1 mSv = 0.001 Sv = $(1 \times 10^{-3})$ Sv

**equivalent dose (H) = absorbed dose (D) x weighting factor ($w_r$)**




$$H = D\,w_r$$

$$D = \frac{H}{w_r}$$

$$w_r = \frac{H}{D}$$

# ................. Equivalent Dose (continued)

## "Equivalent Dose" Problems With Solutions

A sample of brain tissue, when exposed to slow neutrons [$w_r$ = 2.3] receives an absorbed dose of 3.0 mGy ($3.0 \times 10^{-3}$ Gy).

Calculate the equivalent dose for the brain tissue.

**SOLUTION**

$$H = D w_r$$
$$= (3.0 \times 10^{-3}) \times 2.3$$
$$= \underline{\underline{6.9 \times 10^{-3}\ Sv}}$$
(or $\underline{\underline{6.9\ mSv}}$)

When exposed to fast neutrons [$w_r$ = 10], a sample of kidney tissue receives an equivalent dose of 55 μSv ($55 \times 10^{-6}$ Sv).

Calculate the absorbed dose for the kidney tissue.

**SOLUTION**

$$D = \frac{H}{w_r}$$
$$= \frac{55 \times 10^{-6}}{10}$$
$$= \underline{\underline{5.5 \times 10^{-6}\ Gy}}$$
(or $\underline{\underline{5.5\ \mu Gy}}$)

On exposure to ionising radiation, a sample of skin tissue receives an equivalent dose of 9.2 mSv ($9.2 \times 10^{-3}$ Sv) and an absorbed dose of 4.0 mGy ($4.0 \times 10^{-3}$ Gy).

Calculate the weighting factor for the ionising radiation.

**SOLUTION**

$$w_r = \frac{H}{D}$$
$$= \frac{9.2 \times 10^{-3}}{4.0 \times 10^{-3}}$$
$$= \underline{\underline{2.3}}$$

## "Total Equivalent Dose" Problem With Solution

A sample of lymph tissue is exposed to three types of ionising radiation at the same time - beta particles [$w_r$ = 1], slow neutrons [$w_r$ = 2.3] and fast neutrons [$w_r$ = 10].

The tissue sample receives an absorbed dose of 2.5 mGy ($2.5 \times 10^{-3}$ Gy) due to the beta particles, an absorbed dose of 2.0 mGy ($2.0 \times 10^{-3}$ Gy) due to the slow neutrons and an absorbed dose of 0.14 mGy ($0.14 \times 10^{-3}$ Gy) due to the fast neutrons.

Calculate the total equivalent dose received by the lymph tissue sample.

**SOLUTION**

$$H_{total} = D w_r(\text{beta particles}) + D w_r(\text{slow neutrons}) + D w_r(\text{fast neutrons})$$
$$[(2.5 \times 10^{-3}) \times 1] + [(2.0 \times 10^{-3}) \times 2.3] + [(0.14 \times 10^{-3}) \times 10]$$
$$(2.5 \times 10^{-3}) + (4.6 \times 10^{-3}) + (1.4 \times 10^{-3})$$
$$= \underline{\underline{8.5 \times 10^{-3}\ Sv}}$$
(or $\underline{\underline{8.5\ mSv}}$)

## "Absorbed Dose and Equivalent Dose" Problem With Solutions

When exposed to slow neutrons [$w_r$ = 2.3], a 0.30 kg sample of muscle tissue absorbs 1.2 μJ ($1.2 \times 10^{-6}$ J) of energy.

For this tissue sample, calculate:

(a) the absorbed dose

(b) the equivalent dose

**SOLUTIONS**

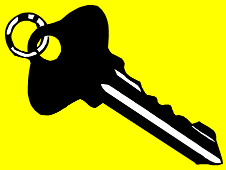
(a)
$$D = \frac{E}{m}$$
$$= \frac{1.2 \times 10^{-6}}{0.30}$$
$$= \underline{\underline{4.0 \times 10^{-6}\ Gy}}$$
(or $\underline{\underline{4.0\ \mu Gy}}$)

(b)
$$H = D w_r$$
$$= (4.0 \times 10^{-6}) \times 2.3$$
$$= \underline{\underline{9.2 \times 10^{-6}\ Sv}}$$
(or $\underline{\underline{9.2\ \mu Sv}}$)

Spread 9

# Radiation Doses - Equivalent Dose Rate...

**Key Learning Objectives** **To find out:**



- the meaning of the term 'equivalent dose rate' and the unit it is measured in
- how to solve problems involving 'equivalent dose rate', 'equivalent dose' and 'time of exposure' to the absorbed ionising radiation

## Equivalent Dose Rate

For the human body, as the time of exposure to ionising radiation increases, the level of biological harm to the body increases.

It is therefore important to take into account the 'time of exposure' to the ionising radiation.

To achieve this, the 'equivalent dose' of ionising radiation received by the body tissue is divided by the 'time of exposure' to the radiation - this gives a quantity known as the 'equivalent dose rate' ($\dot{H}$). This is the equivalent dose of ionising radiation received per unit time.

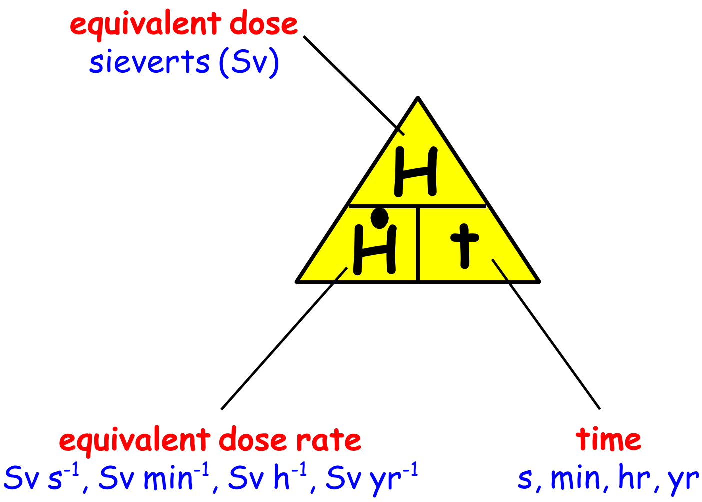
**Equivalent dose rate is the equivalent dose of ionising radiation received by a sample of human body tissue per unit time.**

Equivalent dose rate is often measured in sieverts per second ($Sv\ s^{-1}$), sieverts per minute ($Sv\ min^{-1}$), sieverts per hour ($Sv\ h^{-1}$) or sieverts per year ($Sv\ yr^{-1}$)

**NOTE**

Because 1 sievert is a very large quantity, typical equivalent dose rate values are often expressed in micro-sieverts per second/minute/hour/year or in milli-sieverts per second/minute/hour/year.

$$\text{equivalent dose rate } (\dot{H}) = \frac{\text{equivalent dose (H)}}{\text{time (t)}}$$




$$\dot{H} = \frac{H}{t}$$

$$H = \dot{H}t$$

$$t = \frac{H}{\dot{H}}$$

## "Equivalent Dose Rate" Problems With Solutions

While exposed to ionising radiation for a time of 25 s, a sample of spleen tissue receives an equivalent dose of 50 μSv ($50 \times 10^{-6}$ Sv).

Calculate the equivalent dose rate for the spleen tissue.

**SOLUTION**

$$\dot{H} = \frac{H}{t}$$

$$= \frac{50 \times 10^{-6}}{25}$$

$$= \underline{\underline{2.0 \times 10^{-6}\ \text{Sv s}^{-1}}}$$

(or $\underline{\underline{2.0\ \mu\text{Sv s}^{-1}}}$)

Over a period of 2.0 minutes, the equivalent dose rate for a sample of tongue tissue was found to be 4.0 mSv min$^{-1}$ ($4.0 \times 10^{-3}$ Sv min$^{-1}$).

Calculate the equivalent dose received by the tongue tissue.

**SOLUTION**

$$H = \dot{H}t$$

$$= (4.0 \times 10^{-3}) \times 2.0$$

$$= \underline{\underline{8.0 \times 10^{-3}\ \text{Sv}}}$$

(or $\underline{\underline{8.0\ \text{mSv}}}$)

The equivalent dose rate for a sample of tendon tissue exposed to ionising radiation was 5.0 μSv h$^{-1}$ ($5.0 \times 10^{-6}$ Sv h$^{-1}$). The tissue sample received an equivalent dose of 7.5 μSv ($7.5 \times 10^{-6}$ Sv).

Calculate the time for which the tendon tissue was exposed to the ionising radiation.

**SOLUTION**

$$t = \frac{H}{\dot{H}}$$

$$= \frac{7.5 \times 10^{-6}}{5.0 \times 10^{-6}}$$

$$= \underline{\underline{1.5\ \text{h}}}$$

## "Total Equivalent Dose and Equivalent Dose Rate" Problem With Solutions

Over a time of 5.0 hours, a sample of colon tissue is exposed continuously to three types of ionising radiation - alpha particles [$w_r = 20$], beta particles [$w_r = 1$] and fast neutrons [$w_r = 10$].

During this time, the tissue sample receives an absorbed dose of 0.20 mGy ($0.20 \times 10^{-3}$ Gy) due to the alpha particles, an absorbed dose of 2.5 mGy ($2.5 \times 10^{-3}$ Gy) due to the beta particles and an absorbed dose of 0.15 mGy ($0.15 \times 10^{-3}$ Gy) due to the fast neutrons.

(a) Calculate the total equivalent dose received by the colon tissue sample.

(b) Calculate the equivalent dose rate for the colon tissue sample.

**SOLUTIONS**

(a) $$H_{total} = D\,w_r(\text{alpha particles}) + D\,w_r(\text{beta particles}) + D\,w_r(\text{fast neutrons})$$

$$[(0.20 \times 10^{-3}) \times 20] + [(2.5 \times 10^{-3}) \times 1] + [(0.15 \times 10^{-3}) \times 10]$$

$$(4.0 \times 10^{-3}) + (2.5 \times 10^{-3}) + (1.5 \times 10^{-3})$$

$$= \underline{\underline{8.0 \times 10^{-3}\ \text{Sv}}}$$ (or $\underline{\underline{8.0\ \text{mSv}}}$)

(b) $$\dot{H} = \frac{H}{t}$$

$$= \frac{8.0 \times 10^{-3}}{5.0}$$

$$= \underline{\underline{1.6 \times 10^{-3}\ \text{Sv h}^{-1}}}$$

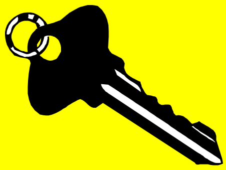
(or $\underline{\underline{1.6\ \text{mSv h}^{-1}}}$)

Spread 10

# Equivalent Dose - Source Comparison



**Key Learning Objectives** To find out:



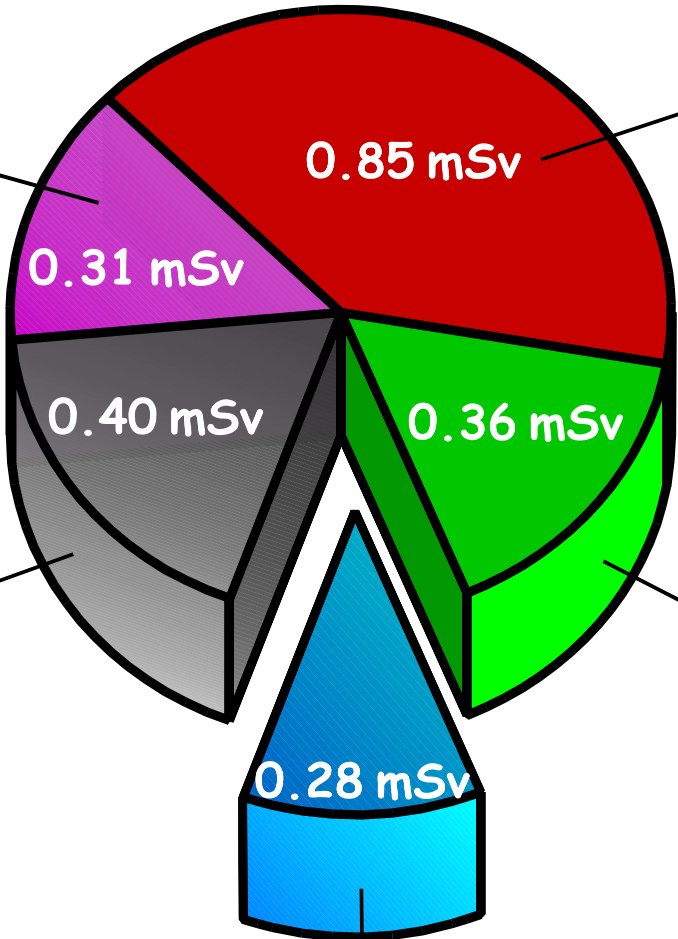
- values for the 'equivalent dose' we typically receive every year in the U.K. from each type of background radiation
- the value for the 'average annual equivalent dose' in the U.K. due to background radiation
- the value for the 'annual effective equivalent dose safety limit' (in addition to background radiation) for members of the public in the U.K.
- the value for the 'annual effective equivalent dose safety limit' (in addition to background radiation) for radiation workers in the U.K.

## 1) Comparison of Equivalent Dose Due to a Variety of Natural and Artificial Sources in the U.K.

The pie chart on page 7 of this booklet compares, in percentage terms, the equivalent dose of background radiation we typically receive each year in the U.K. from different sources.

The 3D version below makes the same comparison - but in terms of equivalent dose values.

**All values are in mSv. (1 mSv = 1 x $10^{-3}$ Sv).**






ALL EQUIVALENT DOSE VALUES ARE APPROXIMATE - THEY VARY SLIGHTLY, DEPENDING ON WHERE YOU LIVE IN THE U.K.

# Annual Equivalent Dose Values/Limits in the U.K.

## 2) Average Annual Equivalent Dose in the U.K. Due to Background Radiation

Adding up the equivalent dose values shown by the pie chart on the opposite page:

$$0.85 + 0.36 + 0.28 + 0.40 + 0.31 = 2.2\ mSv$$

This shows that, in the U.K., the average annual equivalent dose that a person receives from background radiation is **2.2 mSv**.

Therefore, the average annual equivalent dose rate in the U.K. is **2.2 mSv $yr^{-1}$**.

These are average values because the level of background radiation in the U.K. varies slightly - it depends on where you live.

## 3) Annual Effective Equivalent Dose Safety Limit in the U.K. for Members of the Public and Radiation Workers

An **annual effective equivalent dose safety limit** has been set for exposure to ionising radiation by members of the public in the U.K.

The value is **1 mSv** (in addition to background radiation).

A higher **annual effective equivalent dose safety limit** has been set for exposure to ionising radiation by workers in certain specialised occupations in the U.K., e.g., radiation workers in a nuclear power station.

The value is **20 mSv** (in addition to background radiation).

# Spread 11 Applications of Nuclear Radiation (1) .....

**Key Learning Objective**

**To find out:**

- some medical, industrial and domestic uses for nuclear radiation

*The application (use) of nuclear radiation is widespread in medicine and industry. It also has one important application in our homes.*

*This double-page spread details some of these applications (uses).*

## Nuclear Radiation - Medical, Industrial and Domestic Uses

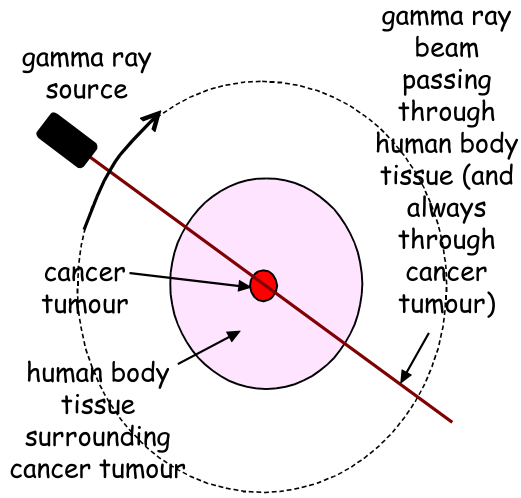
## *Medical Uses*

### *1) Cancer Treatment (Radiotherapy)*

Radiotherapy is used to kill cancer cells that have formed a tumour inside the human body (or to damage the cancer cells sufficiently so they will not be able to divide further).

The patient lies still while a source of gamma radiation is continuously rotated around them in a complete circle. A narrow beam of gamma radiation from the source is directed so it will always pass through the cancer tumour from every angle in the circle, while only passing through each section of the surrounding body tissue twice every rotation.

In this way, the cancer tumour receives a high dose of gamma radiation while the surrounding body tissue only receives a small, far-less damaging dose.






### *2) Tracing Blood Flow Around the Human Body*



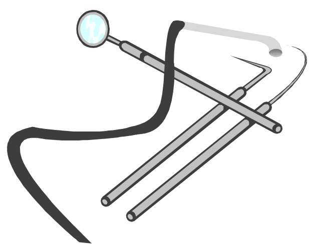

A tracer is a liquid treated so it emits gamma radiation. It can be injected into a system such as the human bloodstream. The movement of the tracer through that system can be followed by detecting the gamma radiation the tracer emits.

Doctors inject a tracer into a patient's bloodstream so they can follow the flow of blood around that patient's body using a gamma camera.

Any 'blockage' or region of unusually-high blood flow (such as a cancer tumour) may thus be detected.

### *3) Sterilising Surgical Instruments*

Gamma radiation is used to sterilise (kill bacteria on) surgical instruments before the instruments are used to carry out an operation.



# Industrial Uses

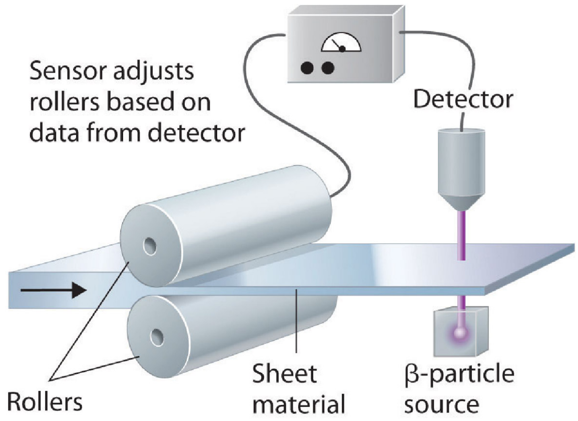
## 1) Monitoring the Thickness of Sheet materials

As soon as paper or linoleum floor covering is manufactured, it is passed between two rollers to achieve the correct thickness of product.

As the product leaves the rollers, a beam of beta radiation is passed through it, from a source to a beta particle detector.

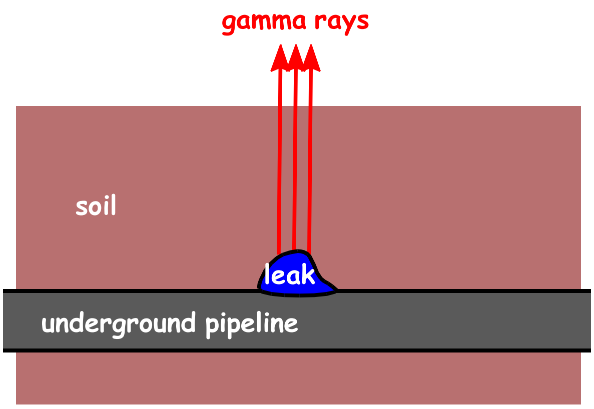
If the product thickness increases, less beta particles will be able to pass through it, so the reading on the beta particle detector will decrease - and vice versa.

Data from the beta particle detector is continuously passed to a computer that controls the force exerted on the product by the rollers - this allows the correct thickness of product to be maintained.




## 2) Detecting Leaks in Underground Pipelines

diagram copyright M. Cunningham




The position of a leak in an underground industrial pipeline can be detected by adding a gamma ray-emitting tracer to the liquid flowing through the pipe.

As the liquid in the pipe leaks from it into the surrounding soil, the tracer will also pass into the soil. Gamma radiation from the tracer will travel up through the soil to the surface.

A person walking on the soil surface above the pipeline will be able to detect this gamma radiation (and therefore the position of the leak in the pipeline) if they are carrying a portable Geiger-Muller tube with counter. The reading on the counter will increase significantly when the Geiger-Muller tube is directly above the leak.

## 3) Detecting Cracks or Gaps in Welds

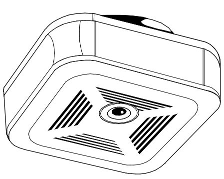
Sections of metal pipeline are joined together by welds - areas where the metal at the seams has been melted together.

Passing a beam of gamma radiation through the welds in the metal pipes, from a source to a gamma detector, enables cracks or gaps in the welds to be detected.

At a crack or gap in a weld, the reading on the gamma detector will increase.

# Domestic (Household) Use

## Smoke Alarms



Smoke alarms contain a small, weak source of alpha radiation. Alpha particles emitted from the source ionise the nearby air molecules inside the alarm - this releases electrons. These electrons create an electric current in an electronic control circuit.

If smoke enters the alarm, the smoke particles absorb many of the alpha particles emitted from the alpha source. This reduces the ionisation process, so the size of the electric current in the electronic control circuit decreases. The control circuit then switches on a buzzer to warn of the presence of smoke.

Spread 12

# Applications of Nuclear Radiation (2) .....

**Key Learning Objective** **To find out:**

- the process that takes place during a 'nuclear fission' reaction
- what happens during a nuclear 'chain reaction'
- how the heat energy released by a nuclear 'chain reaction' is converted to electrical energy in the 'nuclear fission reactor' of a nuclear power station

*One vitally-important application (use) of nuclear radiation is the generation of electrical energy (electricity).*

*This double-page spread details how electrical energy is generated as a result of nuclear fission reactions in the nuclear fission reactor of a nuclear power station.*

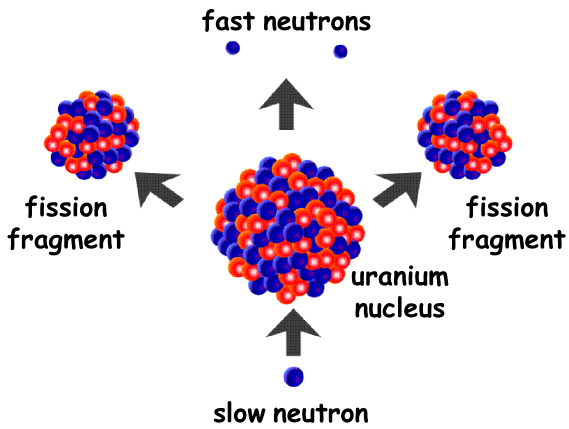
## 1) Nuclear Fission and Nuclear Chain Reactions

In a nuclear power station, nuclear fission reactions take place in a nuclear fission reactor.

A **slow neutron** hits the nucleus (centre) of a uranium atom, causing that nucleus to break up into two smaller parts called fission fragments. Every time this happens, the kinetic energy of the fission fragments is converted to heat energy.

Two or three more **fast neutrons** are also released from the split nucleus.

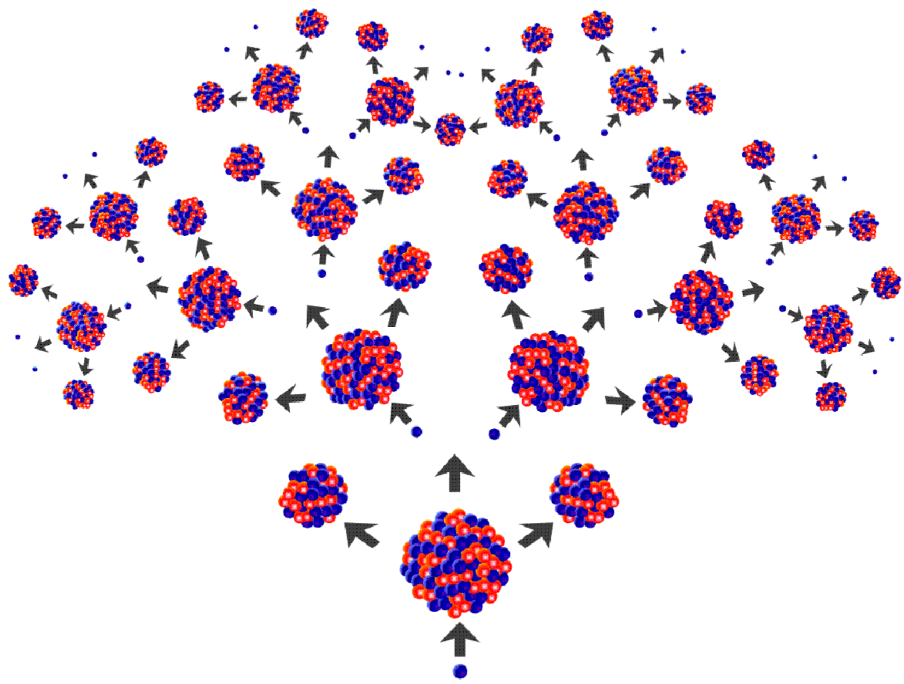
This nuclear fission process is represented by the diagram opposite.




The **fast neutrons** that are released (when slowed down sufficiently to become **slow neutrons**) hit the nuclei of other uranium atoms, causing these nuclei to break up into two fission fragments and release more **fast neutrons** that, once slowed down, cause the process to multiply each time - this is known as a **chain reaction**.

Chain reactions generate a great deal of heat energy.

The chain reaction process is represented by the diagram below:





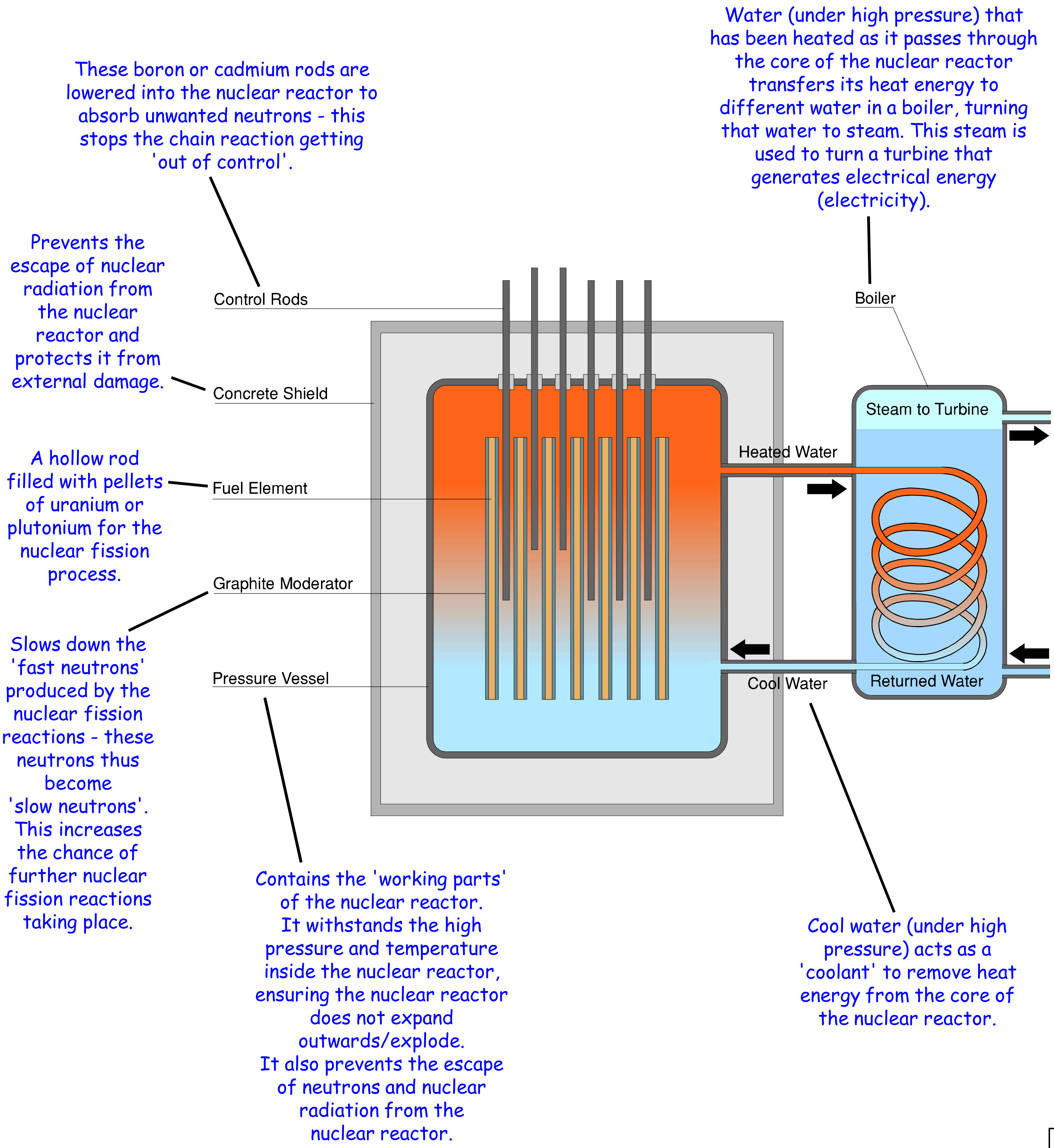
Because the neutrons taking part in the nuclear fission process are released from atomic nuclei, they are classified as 'nuclear radiation'.

## 2) Nuclear Fission and Electricity Generation

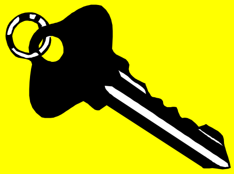
A large part of the electrical energy (electricity) used in the U.K. is generated as a result of nuclear fission reactions in the nuclear fission reactor of a nuclear power station.

The purpose of the nuclear fission reactor is to produce a constant source of heat energy. This heat energy is used to boil water in order to produce high pressure steam. The high pressure steam is used to turn turbine blades connected to generators that convert the kinetic energy of the steam to electrical energy (electricity).

This diagram represents the nuclear fission reactor in a typical nuclear power station. The function of each part is explained.



# Applications of Nuclear Radiation (3) .....



**Key Learning Objective** **To find out:**

- the process that takes place during a 'nuclear fusion' reaction
- the physical conditions necessary for 'nuclear fusion' to take place and the reason why these are necessary
- the name of the physical state in which matter exists at the very high temperatures required for 'nuclear fusion'
- why it is necessary to contain the plasma involved in the 'nuclear fusion' reactions carried out by physicists/engineers on earth and how this is achieved
- how energy is extracted from the 'nuclear fusion' process carried out on earth

*A process called nuclear fusion has great potential to meet our future energy requirements. It is this process that generates heat and light in the stars. However, nuclear fusion is very difficult to carry out and control on earth.*

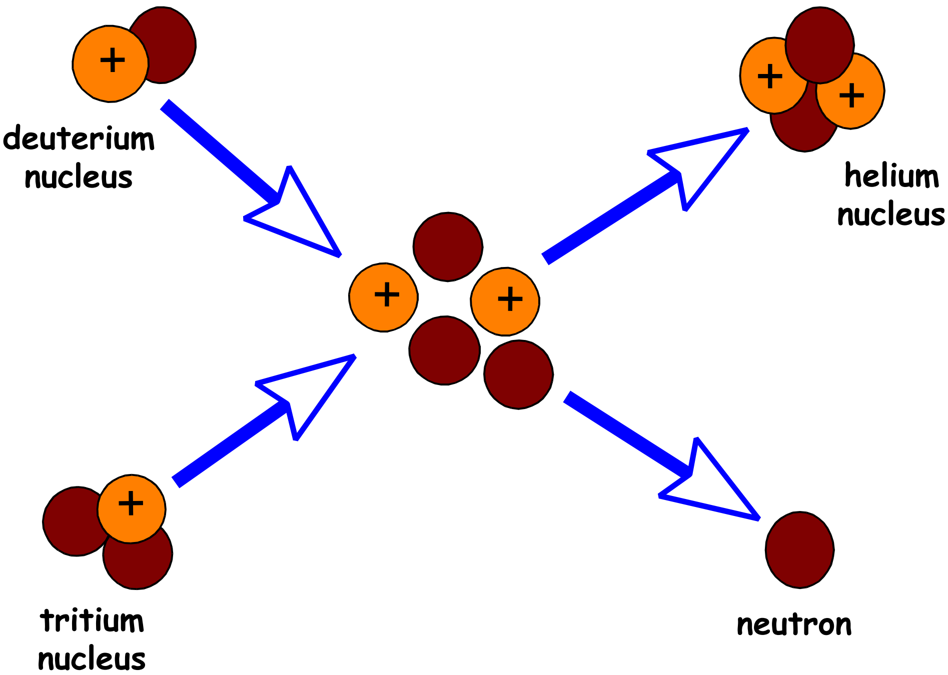
*This double-page spread explains the process of nuclear fusion and some of the problems physicists/engineers face to make it viable on earth.*

## 1) Nuclear Fusion

In a nuclear fusion reaction, two small positively-charged atomic nuclei collide together at very high speed. The two small atomic nuclei combine together to form one larger atomic nucleus. A single neutron is usually released as well.

When nuclear fusion is carried out by physicists/engineers on earth, deuterium and tritium nuclei are commonly used for collision - these are types of hydrogen. In this case, the larger atomic nucleus formed is helium. This is illustrated by the diagram below:





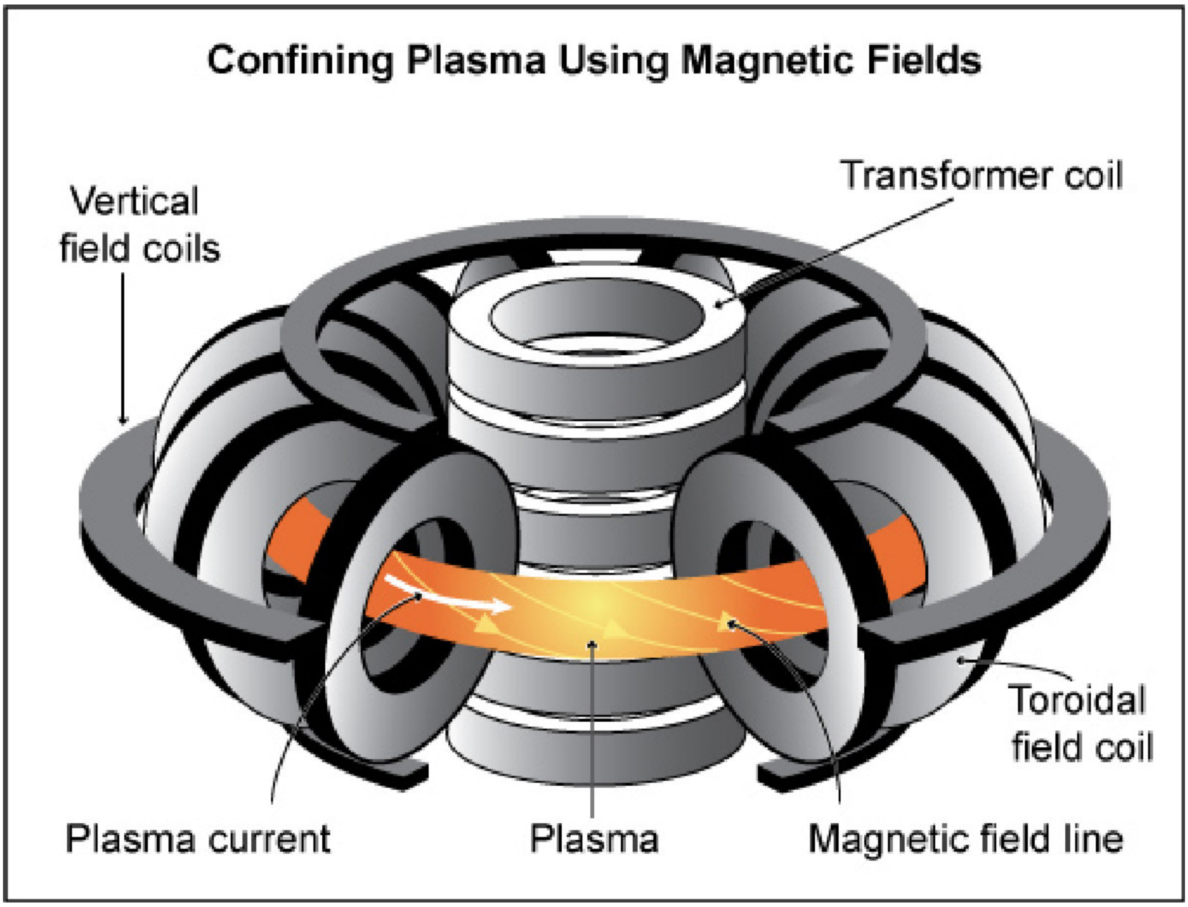

Nuclear fusion reactions can only take place at very high pressures and very high temperatures - typically above 100 million °C ($1 \times 10^8$ °C). These physical conditions are needed to overcome the strong repulsion force acting between the two small positively-charged colliding nuclei as they approach one another.

At such high temperatures, matter exists in a physical state known as plasma - a high energy mixture of small neutral particles, larger positively-charged atomic nuclei and the electrons these positively-charged atomic nuclei have lost.

## 2) Plasma Containment - A Major Problem

A major problem with the nuclear fusion process carried out by physicists/engineers on earth is to find a material for the inside walls of the plasma container that will not melt due to the very high temperature.

This problem is overcome by keeping the plasma out of contact with the inside walls of a container known as a Tokamak. This has the shape of a 'ring doughnut', with a hollow vacuum chamber inside, as shown by the diagram below:






Enormously-strong magnetic fields (created by devices called field coils) are used to contain the plasma inside the Tokamak, keeping the plasma away from the internal walls of the vacuum chamber. These magnetic fields also cause the plasma to spiral and move around inside the Tokamak in a circular path.

## 3) Extraction of Energy/Future Potential

The neutrons released as a result of nuclear fusion have a great deal of kinetic energy. These neutrons can be extracted from the process and their kinetic energy converted to heat energy.

Should the process of nuclear fusion be developed successfully by physicists/engineers on earth, this heat energy could be used to boil water in order to produce high pressure steam. The high pressure steam could be used to turn turbine blades connected to generators that would convert the kinetic energy of the steam to electrical energy (electricity).

Because the deuterium and tritium atoms required for the nuclear fusion process are present in water, and water is in abundant supply, the potential of nuclear fusion as a low-cost and plentiful source of our energy in the future is enormous.