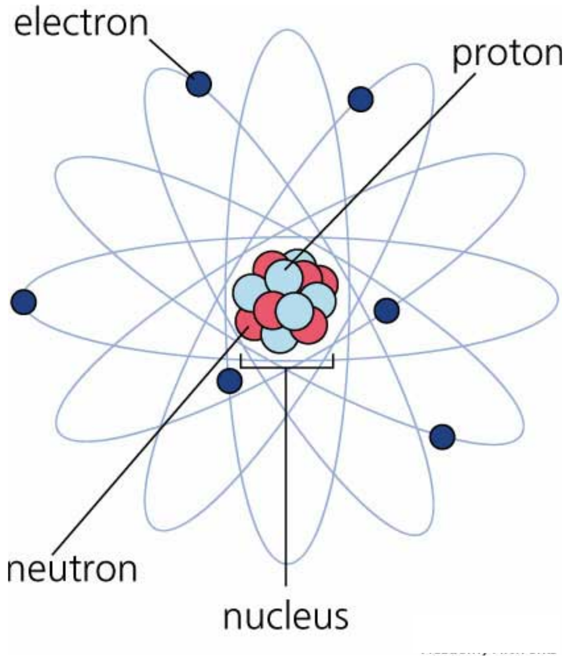
National 5 Physics

Radiation

THE ATOM

All matter consists of atoms, however atoms themselves are made up of several different particles. In the middle of an atom is a very small, very dense object called the **nucleus**. The nucleus is made up of positively charged **protons** and electrically neutral **neutrons**. The nucleus is surrounded by negative **electrons**.



A single atom is about 0.1nm across. A nucleus is only a few femto meters ($\times 10^{-15}$m) across. If you imagine a football pitch representing an atom the nucleus would be the size of a pea on the centre spot.

Name	Mass	Charge
Proton	1	+1
Neutron	1	0
Electron	0	–1

Ionisation

Ionisation is what we call the **addition** or **removal** of an electron from an atom. This will turn a neutrally charged atom into a positively (removing electrons)or negatively (adding electrons) charged **ion**. Atoms can be ionised in many ways but we are only going to study one — **ionising radiation**.

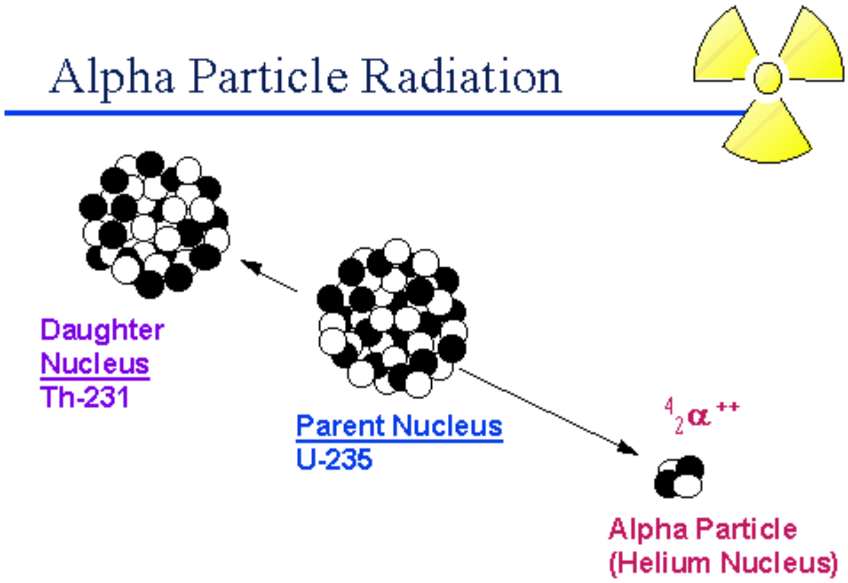
Ionising Radiation

A radiation is considered ionising if it is capable of ionising most atoms. There are three main types:

- Alpha (α)
- Beta (β)
- Gamma (γ)

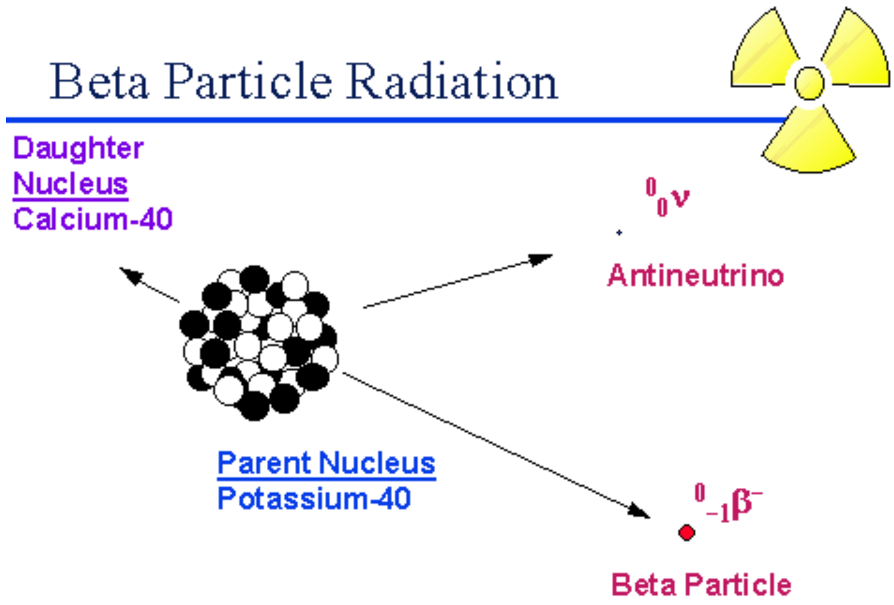
Alpha Particles

Alpha particles are made up of two protons and two neutrons. This means that they are the same as a Helium nucleus (or a He^{+2} ion) — just travelling very quickly. Compared to beta particles and gamma rays, alpha particles are very slow and heavy. Because they are so highly charged, alpha particles are extremely ionising. This means that they will be absorbed very easily — a single sheet of paper or a few centimetres of air is sufficient to absorb nearly all alpha particles. Humans are protected from alpha radiation in the environment by their outer layer of skin, however ingesting or inhaling alpha sources is highly dangerous as the alpha particles are absorbed by organs and tissue.



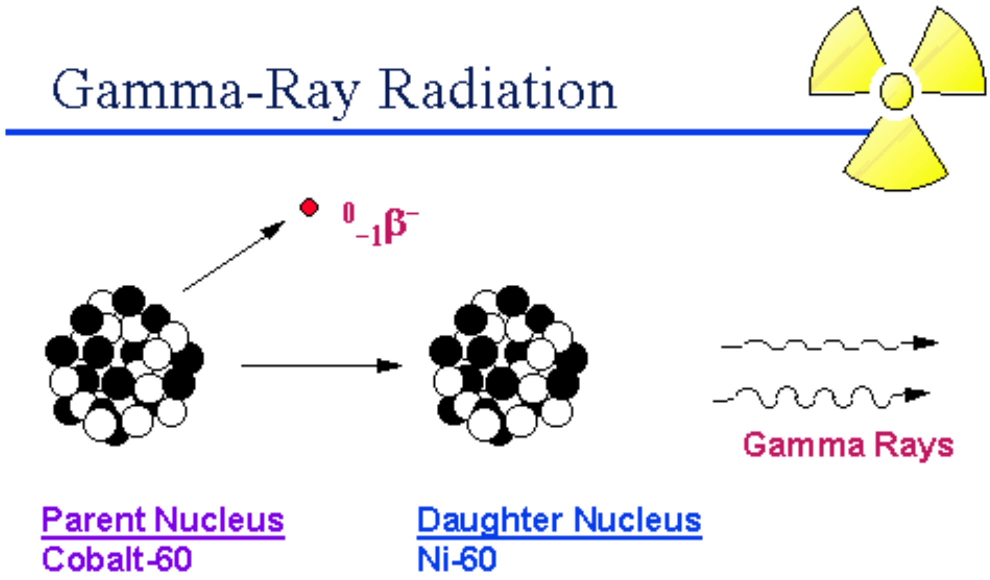
Beta Particles

Beta particles are made up of an electron travelling at high speed. They are much smaller and faster than alpha particles. Beta particles are produced when a neutron decays into a proton. Because beta particles are electrons they are negatively charged. Beta particles are highly ionising — though not as much as alpha particles. Beta particles will be absorbed by a few metres of air or a millimetres of Aluminium.



Gamma Rays

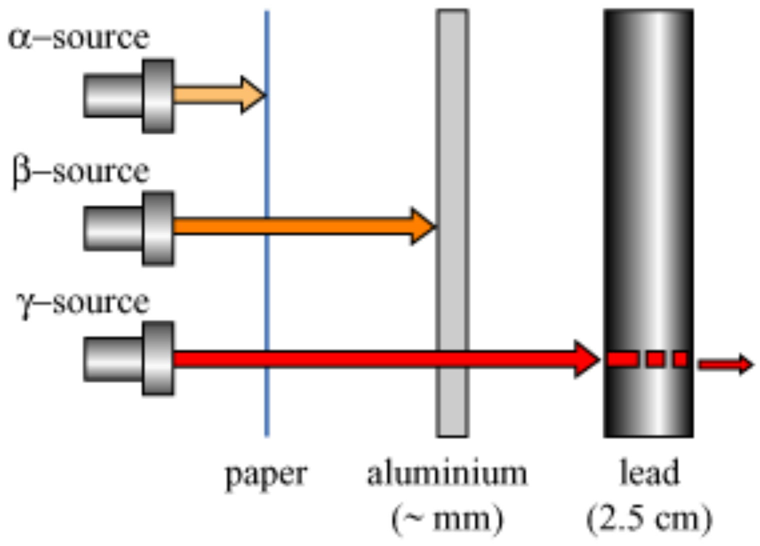
Gamma rays the highest energy, shortest wavelength and highest frequency band of the EM spectrum. Like all kinds of light, gamma rays travel at the speed of light. Gamma rays have no mass or electrical charge so they are only very weakly ionising. Gamma rays are very hard to absorb — you need lots of atoms! Because of this, to absorb gamma rays, a few centimetres of lead or several metres of concrete walls are required.



Summary — Properties of Radiation

Name	Mass	Charge	Made of
Alpha	4	+2	2 protons and 2 neutrons/He nucleus/He^{+2} ion
Beta	almost 0	–1	electrons
Gamma	0	0	EM waves/photons

Summary — Absorption of Radiation



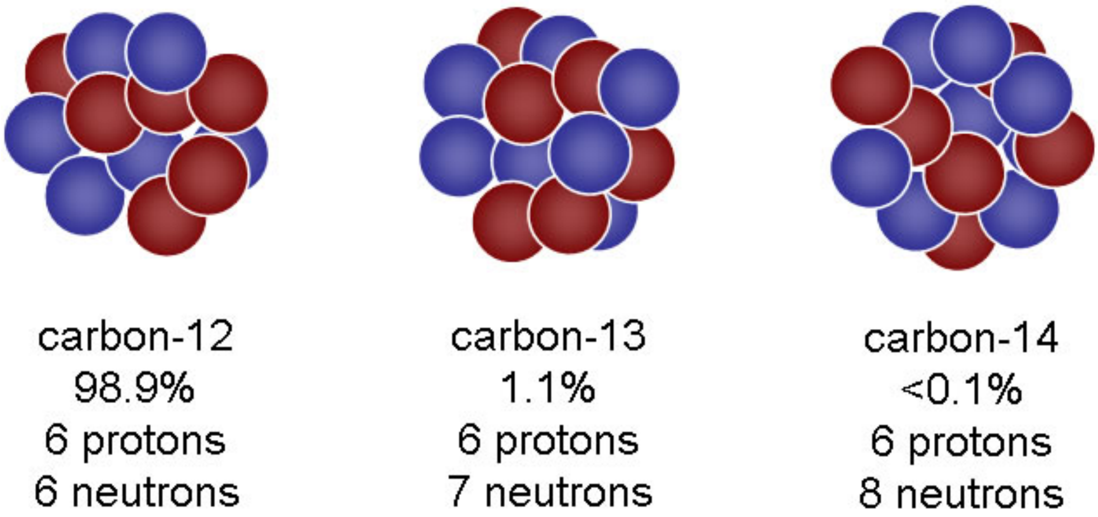
Practice Questions

1. What particles are found in the nucleus of an atom?
2. What particle is found orbiting and atom?
3. What is the electrical charge on an electron?
4. What is the electrical charge on a neutron?
5. What is the electrical charge on a proton?
6. What is the electrical charge on an alpha particle?
7. What is the electrical charge on a beta particle?
8. What is the electrical charge on a gamma ray?
9. Radiation is detected passing through paper but not aluminium or lead. What type of radiation was detected?
10. Another type of radiation is detected passing through paper and aluminium but not lead. What type of radiation was detected?

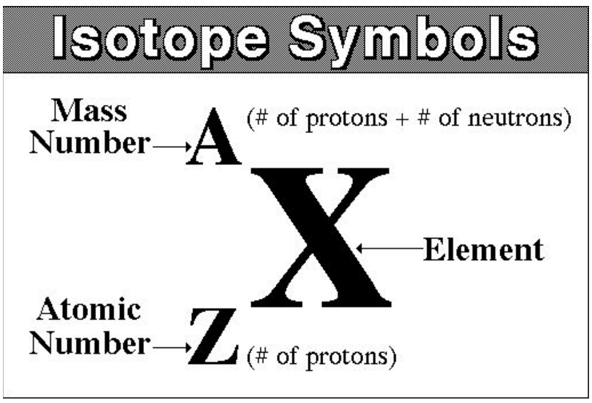
Isotopes

Most radioactivity is caused by an unstable nucleus trying to become stable, releasing radiation in the process. You are familiar with the periodic table of elements (there is a copy in your planner) however this does not tell the whole story. Each element can have variations in the number of neutrons that are in its nucleus — we call these variants **isotopes**.

Below are some of the isotopes of Carbon

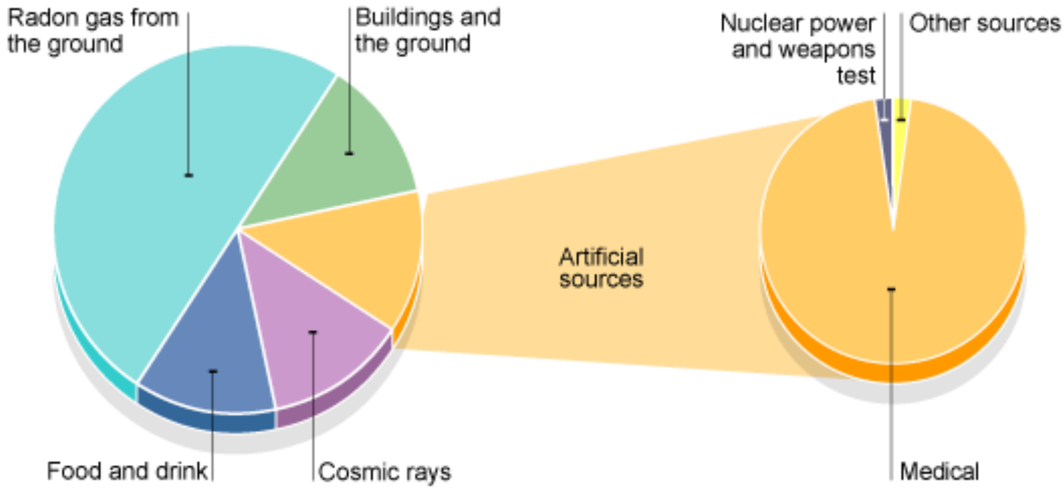


All three have the same number of protons — 6 — but different numbers of neutrons. Isotopes are typically named as their element followed by their atomic mass number (the number of protons and neutrons combined). For instance Carbon–14, Cobalt–60 or Uranium–235. There are a few exceptions, most notably Hydrogen–2, which is known as deuterium, and Hydrogen–3, which is known as tritium.



Background Radiation

There is a small amount of radiation (comprised of all three types) that is emitted all the time. This is known as **background radiation**. It is due to the radioactive decay of various substances all around us. Some of these are natural sources and some are artificial — some are even inside a human body!



Background Radiation Demonstration

Using a Geiger–Müller tube take 3 readings of the background radiation in the lab.

Reading 1: ____________________________

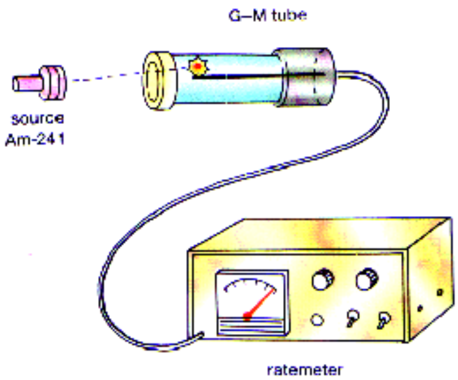
Reading 2: ____________________________

Reading 3: ____________________________

Average background radiation level = __________________ counts per minute

Detection of Ionising Radiation

All forms of ionising radiation will turn a **photographic plate or film** dark. Radiation workers wear a film badge. This measures their exposure to radiation by the amount of darkening of the photographic film. Absorbers such as aluminium, lead and plastic in the windows of the badge enable exposure to the different types of radiation to be measured.



A **Geiger–Müller tube** can be used to detect radiation. The tube contains a gas and has two electrodes at either end with a voltage across them. Radiation causes ions to form in the gas and these form a small pulse of current which is amplified and counted. The greater the amount of radiation, the greater the count rate.

Scintillation detectors work by the radiation striking a suitable material and producing a tiny flash of light. This is amplified by a photomultiplier tube, which results in a burst of electrons large enough to be detected. They can recognise the difference between alpha, beta and gamma radiation.

Effects of Ionising Radiation on Living Tissue

Ionising radiation can be extremely hazardous to living cells. Ionisation of the atoms inside a DNA molecule can cause the DNA to malfunction — causing mutations, such as cancer. Extremely high levels radiation can kill off cells completely leading to severe illness and even death. The following safety procedures should always be considered when working with radioactive sources:

- Limit the time exposed to radiation
- Never touch radioactive sources — use tongs instead
- Never point a radioactive source at someone
- Wash your hands after using a radioactive source
- Maintain a safe distance from the source
- Wear protective clothing (i.e. gloves)
- Stand behind a protective screen or radiation shield

Applications of Radiation

Medical

Although radiation is potentially very harmful to a healthy person the ability of radiation to kill living cells is used in a variety of ways in medicine — as well as other properties of radiation.

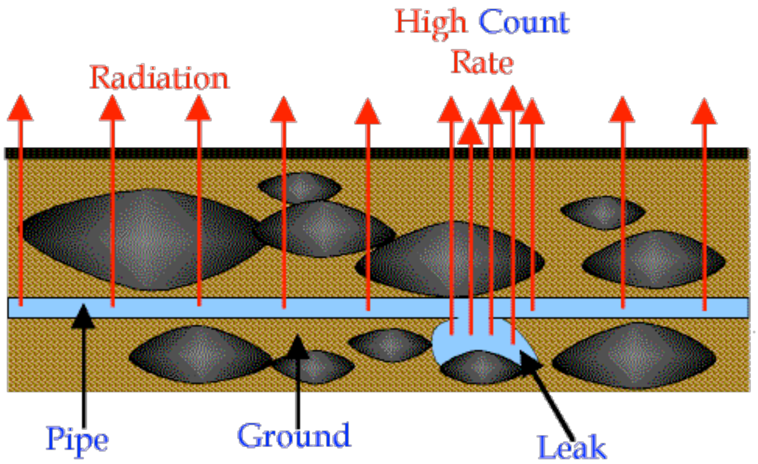
Radiotherapy — This is a treatment for some forms of cancer where the cancer is irradiated (typically with gamma rays). The intense radiation kills the cancer cells However many healthy cells are also damaged, causing patients to feel extremely ill during treatment.

Sterilisation — Medical instruments need to be extremely clean and completely free of any living cells (bacteria) or viruses. Failure to do this can cause patients to become infected, which is potentially fatal. Instruments are exposed to a high intensity gamma source (typically Cobalt–60) that kills all living material on the instrument.

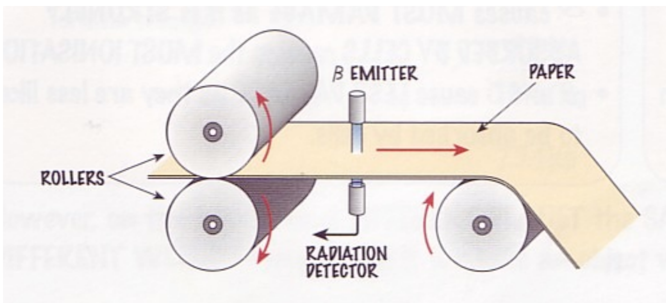
Radioactive Tracers — Radiation can also be used in diagnosis. Radioactive tracers help doctors examine the insides of our bodies. For example: Iodine 131 (a beta source) is used to check if our thyroid glands are working properly. This gland controls the rate at which our body functions. The gland absorbs iodine, so a dose of radioactive iodine (the tracer) is given to the patient. Doctors can then detect the radioactivity of the patient's throat to see how well their thyroid is working.

Industrial

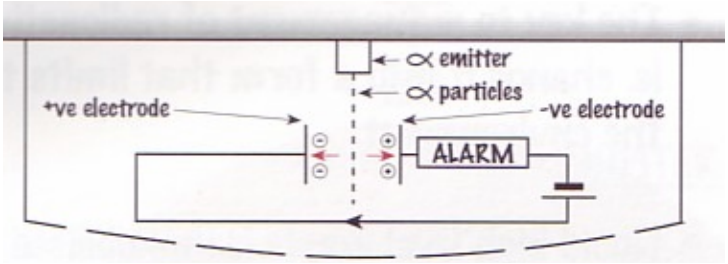
Pipeline Leak Checking — Many long pipelines are used in Scotland to transport oil and gas. A leak in these pipelines would be very costly for businesses in terms of wasted products and environmental clean-up. To make sure that all pipes are sealed or to find a possible leak, a gamma ray source can be put into the oil or gas. If there is a leak, the radioactive source producing gamma rays would leak and be detected by Geiger–Müller tubes in the environment. The type of radiation used has a short lifespan so that the damage to the environment is very small.



Controlling the thickness of sheet materials — Radiation can be used to monitor the thickness of paper as it is being made in a paper mill. Radiation is emitted by an emitter above the sheet. It is detected by a detector on the other side of the sheet. If the thickness of the sheet increases the amount of radiation detected decreases (and vice versa).



Smoke detectors — Most smoke alarms contain a (mildly) radioactive source. The emitted radiation causes ionisation of the air particles and the ions formed are attracted to the oppositely charged electrodes — so a current flows in the circuit.



When smoke enters the space between the two electrodes less ionisation takes place because the radiation is absorbed by the smoke particles. A smaller current than normal flows, and the alarm is designed to sound when this happens.

Practice Questions

1. Why is alpha radiation not used to sterilise medical instruments?
2. How could a radioactive source be used to find a blockage in a kidney?
3. Why are gamma rays used to find leaks in pipelines and not alpha or beta radiation?
4. Why is a beta source used to check the thickness of sheet materials?

Dosimetry

Dosimetry is the measurement of the amount of radiation. We will be looking at three different ways of measuring radioactivity:

- Activity
- Absorbed Dose
- Equivalent Dose

Activity

The activity of a radioactive source is defined as the number of nuclei decaying per second in a radioactive source. It is measured in becquerels (Bq). One becquerel is equal to one decay (or count) per second. There is a formula for activity and it appears on the formula sheet. It is given below:

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

N — Number of decays or counts

t — Time measured in seconds (s)

A — Activity measured in becquerels (Bq)

Absorbed Dose

Not all of the emissions from a radioactive source will be absorbed by a body. Much of the activity from a radioactive source will miss the body and some will pass straight through without being absorbed. It is possible to measure the energy that is absorbed. The amount which is absorbed per 1kg of material is called the **absorbed dose**. The unit of absorbed dose is the gray (Gy). One gray is equal to one joule per kilogram. There is a formula for absorbed dose, it appears on the formula sheet, and is shown below:

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

Energy measured in joules (J)

Mass measured in kilograms (kg)

Absorbed dose measured in grays (Gy)

Practice Questions

1. A radioactive source gives off 300 radioactive emissions in 2 minutes. What is the activity of the source in Becquerels?

2. If 50 J of energy are absorbed by 2 kg of tissue what is the absorbed dose?

3. Calculate the absorbed dose if 20 mJ of energy is absorbed by 400 g of body tissue.

4. A patient of mass 70 kg receives radiotherapy. During the treatment, a tumour of mass 250 g receives 20 J of energy. Calculate the absorbed dose.

Equivalent Dose

The risk to biological tissue from radiation is not just dependant on the amount of energy absorbed and the absorbed dose. The type of radiation is also an important factor. Each type of radiation is assigned a **weighting factor** relating to how dangerous it is. The higher the weighting factor the more dangerous. Some weighting factors are given below:

Radiation	Weighting Factor
Gamma	1
Beta	1
Alpha	20
Protons	2
Neutrons	Varies

The equivalent dose is a measure of how harmful a dose of radiation is. It is found by multiplying the absorbed dose by the correct weighting factor. Equivalent dose is measured in sieverts (Sv). The formula is on the formula sheet and is given below:

$$H = D w_R$$

H: Equivalent dose measured in sieverts (Sv)

D: Absorbed dose measured in grays (Gy)

w_R: Weighting factor

The Health and Safety executive in the UK issue the following guidance on equivalent dosage:

- The average annual background radiation in the UK is 2.2 mSv per year.
- The equivalent dose limit for a member of the public is 1 mSv per year (in addition to the normal background dose)
- The equivalent dose limit for a radiation worker is 20 mSv per year.

Example Equivalent Doses

Equivalent Dose	Source/Effect
0.1 µSv	Eating a banana
1 µSv	Using a CRT monitor for a year
10 µSv	Normal daily dose from background radiation
20 µSv	Chest X–Ray
2 mSv	Head CT scan
4 mSv	Normal yearly dose from background radiation
6 mSv	Spending one hour at the Chernobyl plant (roughly) in 2010
50 mSv	Maximum yearly dose for radiation workers
100 mSv	Minimum dose linked to cancer
400 mSv	Minimum dose to cause radiation poisoning
2 Sv	Severe radiation poisoning
4 Sv	Extreme radiation poisoning — usually fatal
8 Sv	Fatal dose even with treatment
50 Sv	10 minutes next to the Chernobyl reactor after meltdown on 26 April 1986

Practice Questions

1. A radiographer has an absorbed dose of 30 mGy of alpha particles. What is his equivalent dose?

2. A worker in the nuclear industry receives an absorbed dose of 400 µGy from alpha particles and an absorbed dose of 2 mGy from gamma radiation. Calculate the total equivalent dose received.

3. In the course of his work an industrial worker receives a dose equivalent of 200 µSv. Determine the absorbed dose if he is exposed to alpha particles.

Equivalent Dose Rate

The following formula appears on the formula sheet at national 5:

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

This is the formula for equivalent dose rate. This is simply the equivalent dose absorbed per second, i.e. the equivalent dose in sieverts divided by time in seconds. Interestingly in maths placing a dot above a variable actually simply means 'rate of'[1] making the above formula somewhat superfluous.

[1] Actually it is the Newton's notation for the first differential of a quantity with respect to time.

Half–Life

As we already know the nuclei of radioactive atoms are unstable. They break down, emitting radiation and change into a completely different type of atom.

It is not possible to predict when an individual atom might decay as radioactive decay is a random process. In any radioactive source, the activity decreases with time because the number of unstable atoms gradually decreases leaving fewer and fewer atoms to decay.

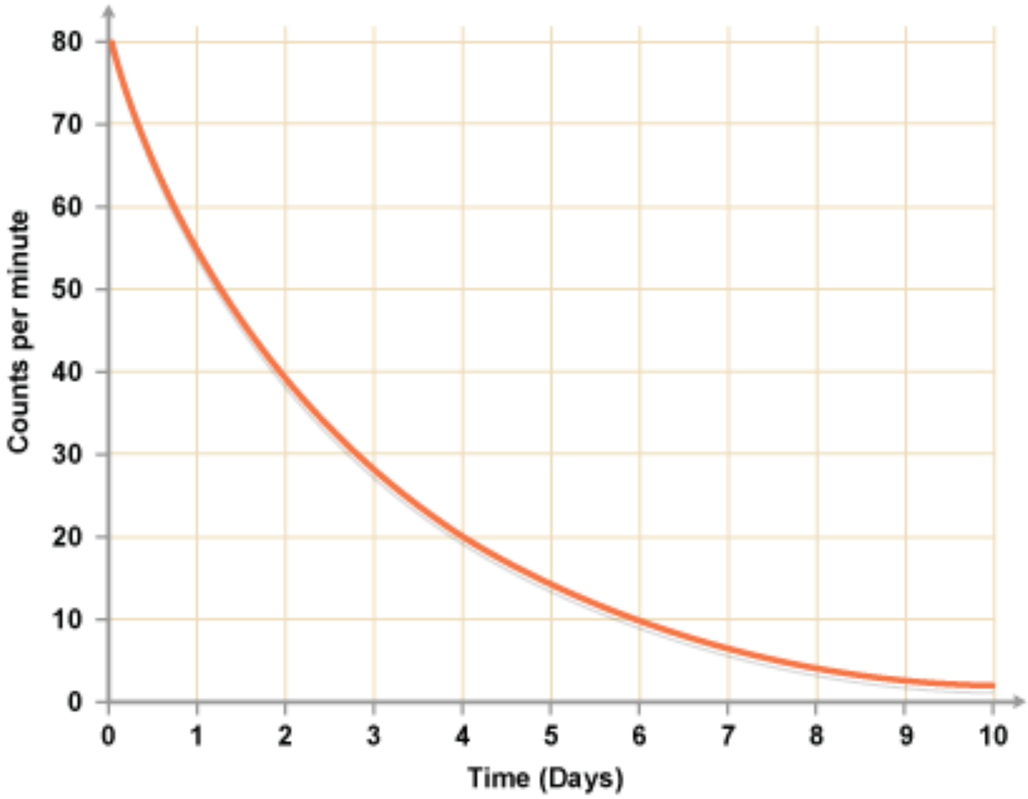
It is possible to measure how long it takes for half the nuclei of a piece of radioactive material to decay. This is called the **half–life** of the radioactive isotope.

Half–life is defined as:

- The time it takes for the number of nuclei in a sample to halve.
- The time it takes for the count rate from a sample containing the isotope to fall to half its starting level.
- The time taken for the activity to fall to half its original value.

Different radioactive isotopes have different half–lives. For example, the half–life of carbon–14 is 5,715 years, but the half-life of francium–223 is just 20 minutes.

It is possible to find out the half–life of a radioactive substance from a graph of the count rate against time. The graph below shows the decay curve for a radioactive substance.



The count rate drops from 80 to 40 counts a minute in two days, so the half-life is two days.

In the next two days, it drops from 40 to 20 — it halves.

In the two days after that, it drops from 20 to 10 — it halves again (and so on).

Example Question

The activity of a source falls from 80 MBq to 5 MBq in 8 days. Calculate its half-life.

- It takes 4 half–lives to decay to 5 MBq.
- Therefore 4 half–lives = 8 days
- So 1 half–life = 2 days

Practice Questions

1. The initial activity of a radioactive isotope is 400 Bq. The sample has a half–life of 2 minutes and is allowed to decay for 8 minutes. Calculate the final activity of the isotope.

2. Radioactive rocks emit radiation, which can be harmful, if exposure to them is not controlled. Some rocks have an activity of 160 Bq and emit radiation over a 3 day period. What is the final activity of these rocks given that their half–life is 12 hours.

3. A sample of radioactive uranium has an initial activity of 600 kBq. After 10 days its activity has dropped to 150 kBq. Use this information to calculate the half–life of the source.

4. Calculate the half–life of a radium spray source, which emits alpha radiation, given that it takes 45 minutes for the activity to drop from 2400 counts per minute to 75 counts per minute.

5. Calculate the initial activity of a radioactive source whose activity falls to 20 kBq in 16 minutes given that it has a half–life of 2 minutes.

6. A radioactive source has a half life of 2 days. What fraction of the sample is left after: 2 days, 6 days and 20 days?

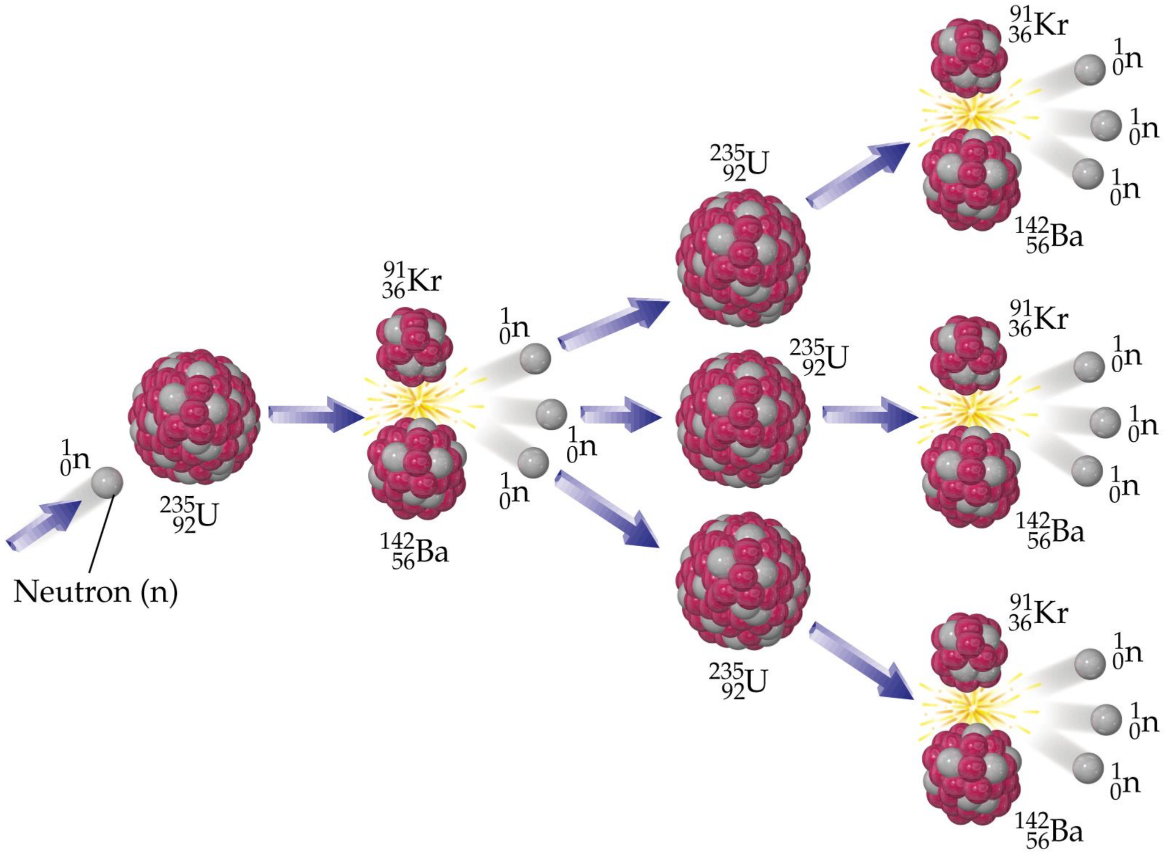
7. The activity of an isotope varies with time as shown below. The count rate is uncorrected for background radiation.

Count rate (per minute)	230	190	160	130	110	95	80	70
Time (hours)	0	1	2	3	4	5	6	7

The background count is 30 counts per minute. Plot a corrected graph of activity against time for the isotope and from it calculate the half–life of the isotope.

Nuclear Fission

Nuclear fission happens when the nucleus of an atom is split in two. This splitting creates two new smaller nuclei, neutrons, and a very large amount of energy. Because fission is caused by neutrons hitting the nucleus, the release of extra neutrons from a fission will in turn cause more fissions in other nuclei. This is known as a **chain reaction**.



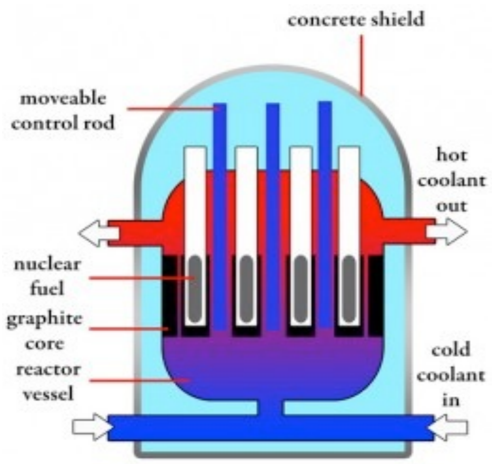
Generating Electricity Using Nuclear Fission

Fission reactions take place in nuclear reactors. The fuel rods are made of uranium-238. The neutrons released are fast moving. A moderator, e.g. graphite, is used to slow them down and increase the chance of further fissions occurring.

These slow (thermal) neutrons cause a chain reaction so that more fissions occur. Control rods, e.g. boron are lowered into the reactor to absorb some of the slow neutrons and keep the chain reaction under control. In the event of an emergency they are pushed right into the reactor core to stop the chain reaction immediately.

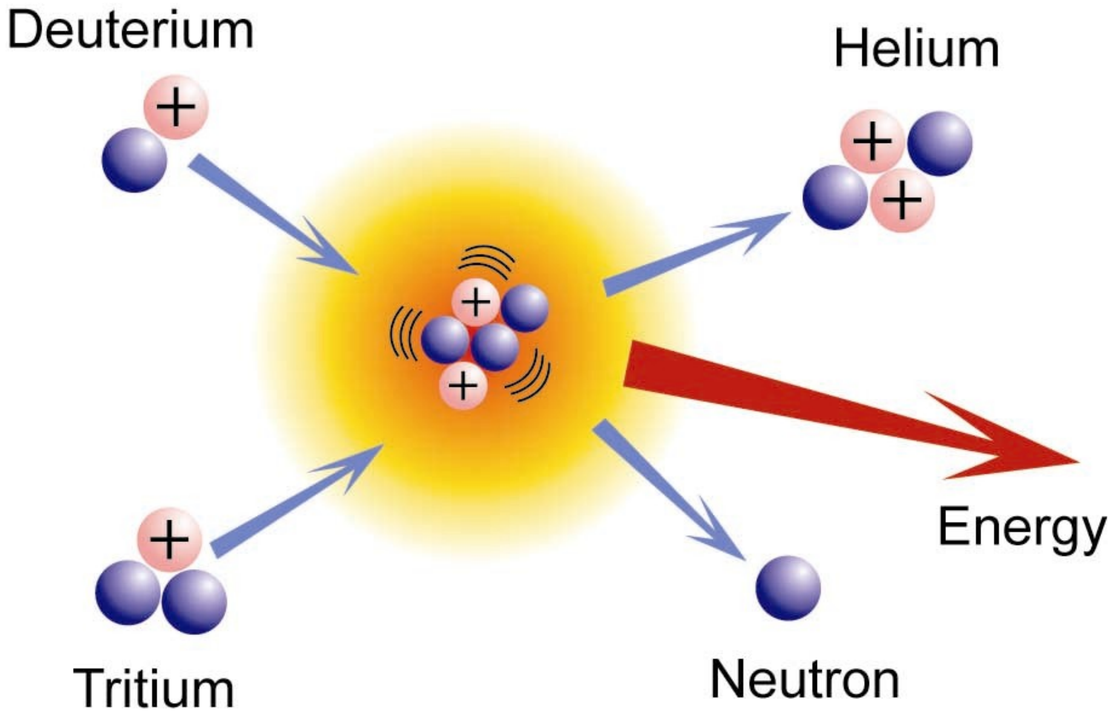
A cooling system is needed to cool the reactor and to transfer heat to the boilers in order to generate electricity. The containment vessel is made of thick concrete which acts as a shield to absorb neutrons and other radiations.

The massive amount of heat generated by the reactor is passed through a heat exchanger to produce steam — which then passes through a turbine — thus generating electricity.



Nuclear Fusion

Nuclear fusion occurs at the extremely high temperatures found inside a star. It is the process of joining two light nuclei (typically hydrogen isotopes) together. This releases very large amounts of energy — as is easily observed by looking at our own Sun.



There is a lot of effort being made to see if the process of nuclear fusion could be replicated under controlled conditions on Earth for the generation of electricity. Nuclear fusion theoretically offers substantial improvements over conventional fission nuclear power plants:

- Improved operational safety
- Far less harmful waste
- Far easier to acquire fuel
- No ability to create materials for nuclear weapons

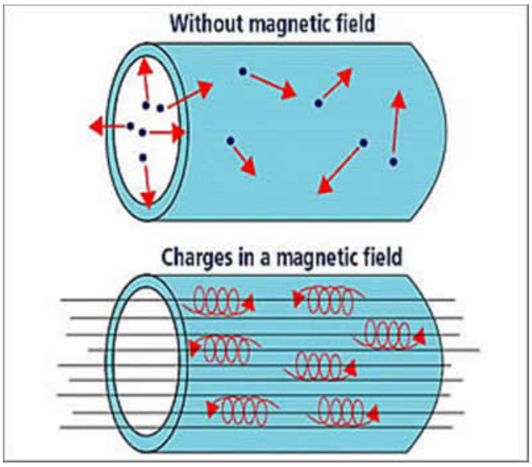
Generating Electricity Using Nuclear Fusion

The Joint European Torus (JET), in Oxfordshire, is Europe's largest fusion device. In this device, deuterium—tritium fusion reactions occur at over 100 million kelvin. Even higher temperatures are required for deuterium–deuterium and deuterium–helium 3 reactions.

To sustain fusion there are three conditions, which must be met simultaneously:

- plasma temperature: 100—200 million kelvin
- energy confinement time: 4—6 seconds
- central density in plasma: $1—2 \times 10^{20}$ particles m^{-3} (approx. 1 mg m^{-3}, i.e. one millionth of the density of air).

In a Tokamak the plasma is heated in a ring-shaped vessel (or torus) and kept away from the vessel walls by applied magnetic fields.



This is known as **magnetic containment**.

Radiation

You need to know:

	✓ ? ✗
What alpha particles, beta particles and gamma rays are	
That radiation can be absorbed by the material it is travelling through	
How easily absorbed each type of radiation is and what materials will absorb most/all of each type of radiation	
What ionisation is	
Which types of radiation are the most and least ionising	
A way to detect radiation	
That radiation can kill living cells or change their nature	
What absorbed dose is and what it is measured in	
How to use the $D = E/m$ formula	
What the radiation weighting factor is	
What equivalent dose is and what it is measured in	
How to use the $H = Dw_r$ formula	
That is risk of biological harm depends on absorbed dose, type of radiation and the part of the body exposed	
What causes background radiation	
What safety precautions should be taken when handling radioactive sources	
What the radioactive hazard sign looks like	
How to reduce the exposure to radiation (by using shielding, limiting time exposed and increasing the distance from the source)	

	✓ ? ✘
That radiation can be used to sterilise medical equipment	
A use of radiation (other than sterilisation)	
What is meant by the activity of a source	
What half life is	
How to do half life calculations	
What nuclear fission and fusion are and how they can be used	