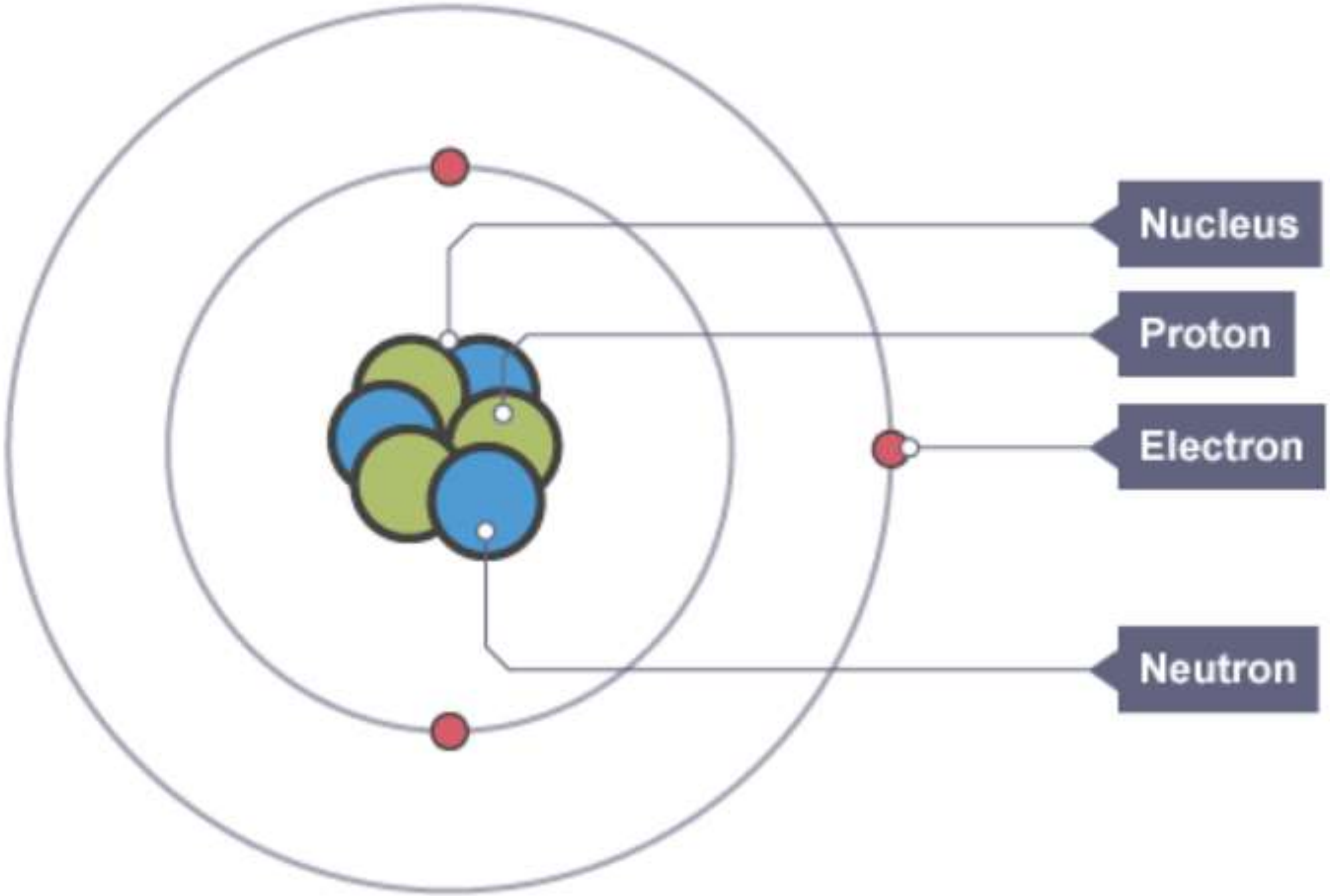
Radioactivity

Structure of the atom:

- The modern view of the **atom** is of a **nucleus** containing **protons** and **neutrons** with smaller **electrons** orbiting outside the nucleus.
- Each particle has its own charge and its own mass.

	Relative charge	Relative mass
Proton	+1	1
Neutron	0	1
Electron	-1	Close to 0 (1/2,000)



Nucleus
Proton
Electron
Neutron

Mass number and atomic number

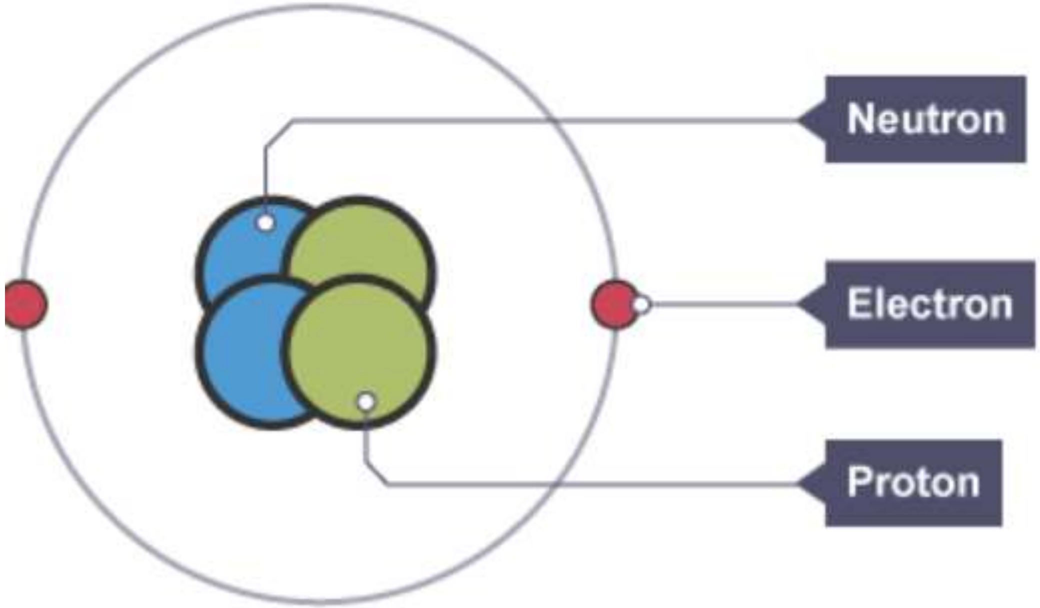
- Protons and neutrons are the heaviest particles in an atom and as a result they make up most of the **mass** of the atom. The mass of electrons is often not considered to be significant.
- The number of protons is what defines the **element**, ie an atom with six protons in its nucleus will always be carbon, and uranium will always have 92 protons.
- **The total number of protons and neutrons is called the mass number and the number of protons is called the atomic number.**
- In a neutral atom, the number of electrons is always the same as the number of protons. If the atom becomes **ionised** however, the number of electrons will change. An ion is an atom that has lost or gained one or more electron.

Atoms and Isotopes

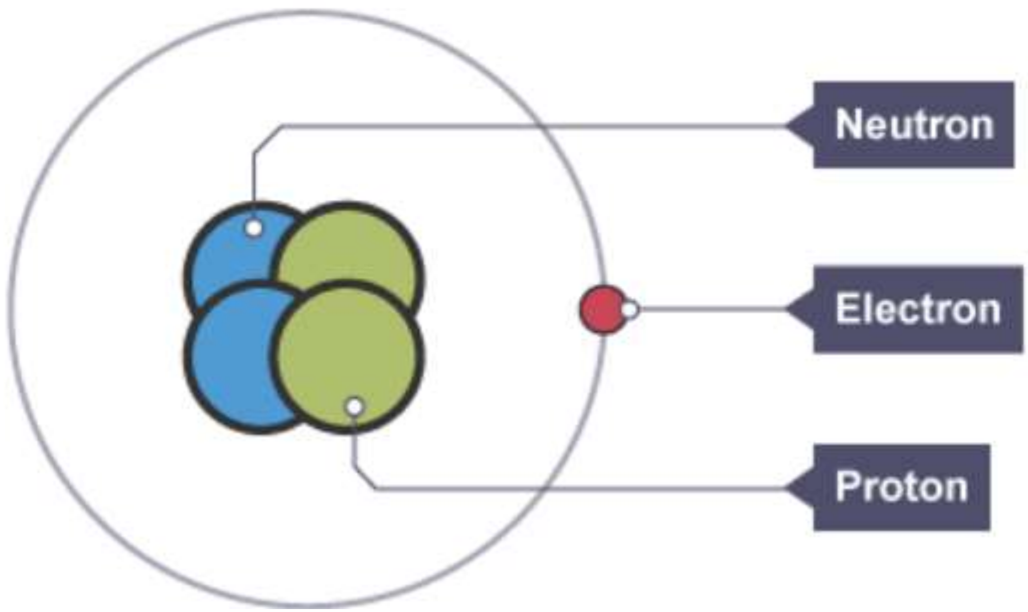
- An **element's atomic number** defines it. An element with 17 **protons** will always be chlorine.
- However an element's **mass numbers** can vary, which means that it can have different numbers of **neutrons**. So although chlorine has a mass number of 35 which means it has 18 neutrons, it can also have a mass number of 37, which means it has 20 neutrons. The different types of chlorine are called **isotopes**.
- **Isotopes are forms of an element that have the same number of protons but different numbers of neutrons.**

Ions

- Normally, atoms are neutral. They have the same number of **protons** in the **nucleus** as they have **electrons** orbiting in the **energy levels** around the nucleus.
- Atoms can, however, lose or gain electrons due to collisions or other interactions. When they do, they form charged particles called **ions**:
- if the atom **loses** one or more electrons, it becomes a **positively-charged ion**
- if the atom **gains** one or more electrons, it becomes a **negatively-charged ion**

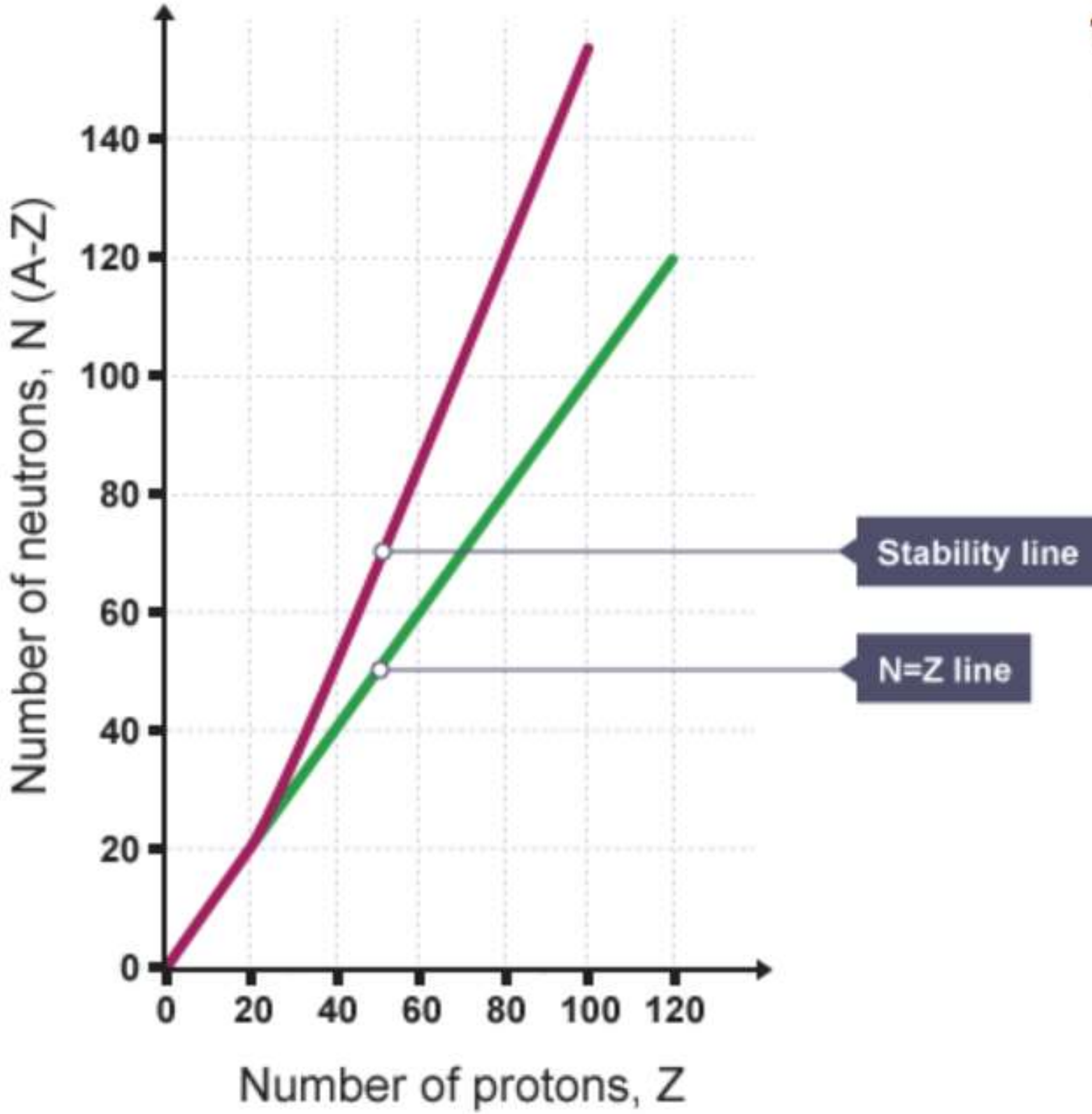

Neutron
Electron
Proton

- A helium atom has two electrons in an energy level outside the nucleus. The atom is neutral as it has two positive protons and two negative electrons.
- A helium atom that has lost or gained an electron is an ion.



Stable Nuclei

- An atom's **nucleus** can only be stable if it has a certain amount of **neutrons** for the amount of **protons** it has.
- Elements with fewer protons, such as the ones near the top of the **periodic table**, are stable if they have the same number of neutrons and protons.
- For example carbon, carbon-12 is stable and has six protons and six neutrons.
- However as the number of protons increases, more neutrons are needed to keep the nucleus stable. For example lead, lead-206 has 82 protons and has 124 neutrons.
- Nuclei with too many, or too few, neutrons do exist naturally but are unstable and will **decay** by emitting **radiation**.



Number of neutrons, N (A-Z)
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Number of protons, Z
Stability line
N=Z line

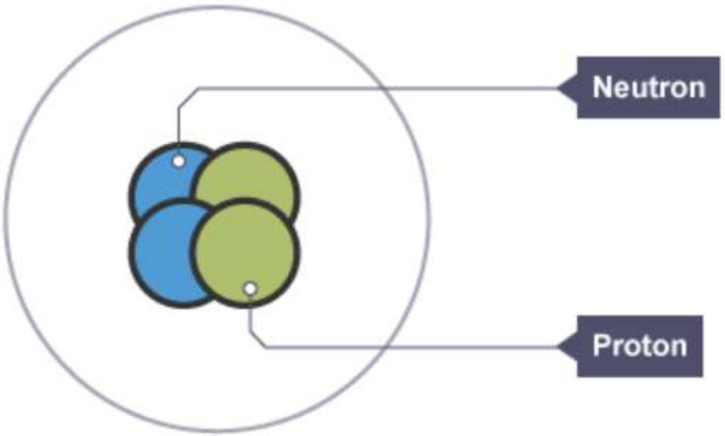
Types of radioactive decay

An unstable nucleus can decay by emitting:

- an **alpha particle**
- a **beta particle**
- a **gamma ray**
- in some cases a single neutron.

Alpha particle

- If the nucleus has too few neutrons, it will emit a 'package' of two protons and two neutrons called an alpha particle.
- An alpha particle is also a Helium-4 nucleus, so it is written as ${}^{4}_{2}He$ and is also sometimes written as ${}^{4}_{2}\alpha$
- Alpha decay causes the **mass number** of the nucleus to decrease by four and the **atomic number** of the nucleus to decrease by two.



Beta particles:

- If the nucleus has too many neutrons, a neutron will turn into a proton and emit a fast-moving **electron**. This electron is called a beta (β) particle - this process is known as **beta radiation**.
- A beta particle has a relative mass of zero, so its mass number is zero, and as the beta particle is an electron, it can be written as . However sometimes it is also written as .
- **The beta particle is an electron but it has come from the nucleus, not the outside of the atom.**
- Electrons are not normally expected to be found in the nucleus but neutrons can split into a positive proton (same mass but positive charge). An electron (which has a negative charge to balance the positive charge) is then ejected at high speed and carries away a lot of energy.
- Beta decay causes the atomic number of the nucleus to increase by one and the mass number remains the same.

Gamma ray:

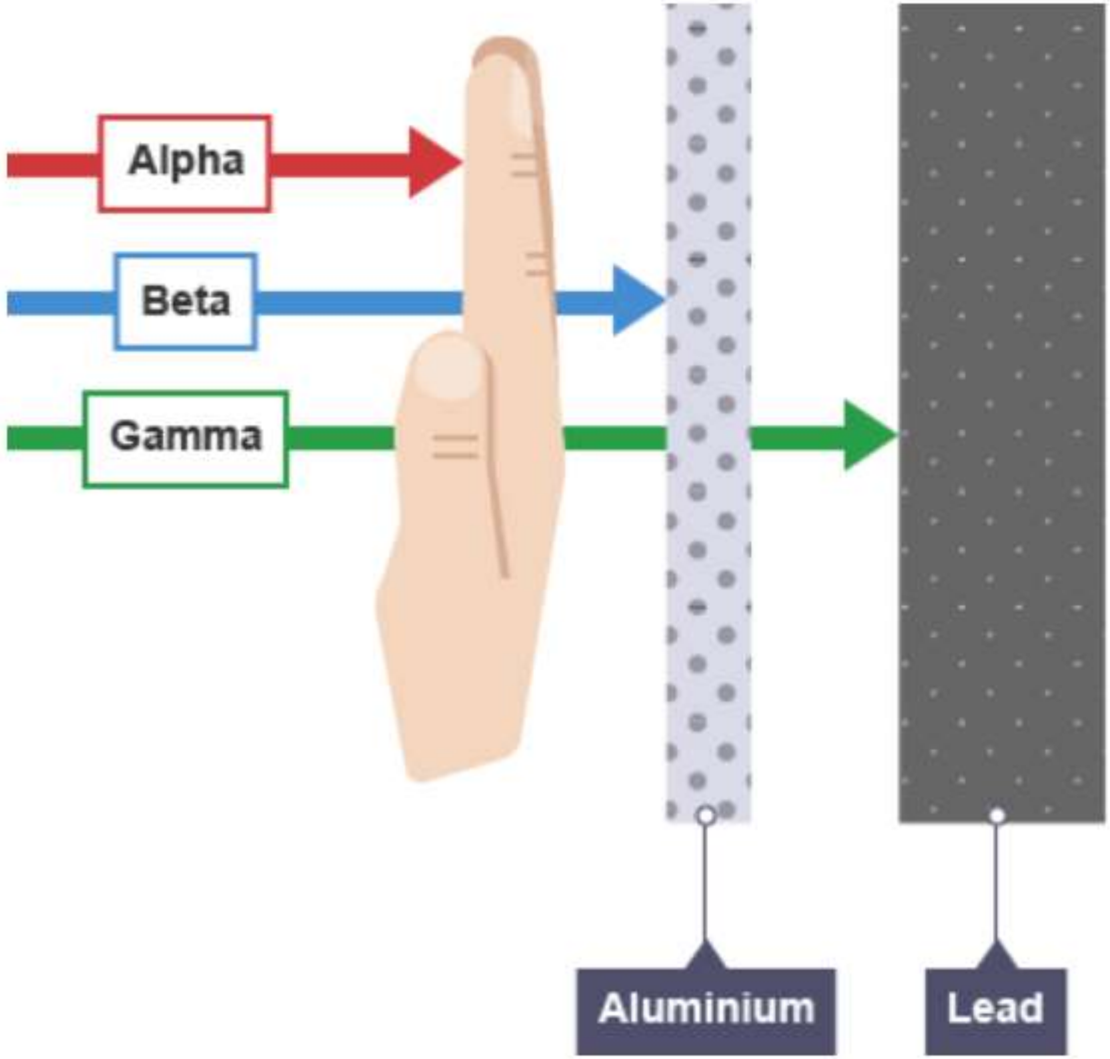
- After emitting an alpha or beta particle, the nucleus will often still be too 'hot' and will lose energy in a similar way to how a hot gas cools down. A hot gas cools by emitting **infrared radiation** which is an **electromagnetic wave**.
- High energy particles will emit energy as they drop to lower **energy levels**. Since energy levels in the nucleus are much higher than those in the gas, the nucleus will cool down by emitting a more energetic electromagnetic wave called a gamma ray.
- Gamma ray emission causes no change in the number of particles in the nucleus meaning both the atomic number and mass number remain the same.

Neutron Emission

- Occasionally it is possible for a neutron to be emitted by **radioactive decay**. This can occur naturally, ie absorption of cosmic rays high up in the atmosphere can result in neutron emission, although this is rare at the Earth's surface. Or it can occur artificially, ie the work done by **James Chadwick** firing alpha particles at Beryllium resulted in neutrons being emitted from that.
- A further example of neutron emission is in nuclear fission reactions, where neutrons are released from the parent nucleus as it splits.
- Neutron emission causes the mass number of the nucleus to decrease by one and the atomic number remains the same.

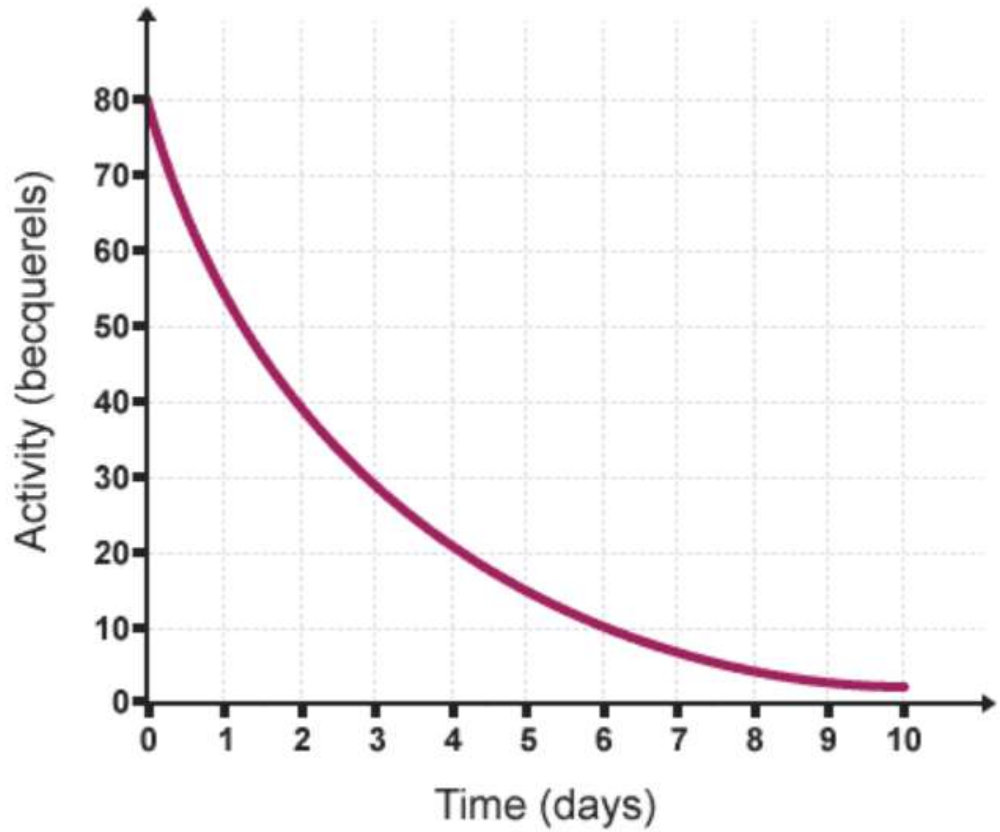
Properties of nuclear radiations

	Symbol	Penetrating power	Ionising power	Range in air
Alpha	α	Skin/paper	High	< 5 centimetre (cm)
Beta	β	3 mm aluminium foil	Low	≈ 1 metre (m)
Gamma	γ	Lead/concrete	Very low	> 1 kilometre (km)


Alpha
Beta
Gamma
Aluminium
Lead

Half time:

- **Radioactive decay** is a random process. A block of **radioactive** material will contain many trillions of **nuclei** and not all nuclei are likely to decay at the same time so it is impossible to tell when a particular nucleus will decay.
- It is not possible to say which particular nucleus will decay next, but given that there are so many of them, it is possible to say that a certain number will decay in a certain time. Scientists cannot tell when a particular nucleus will decay, but they can use statistical methods to tell when half the unstable nuclei in a sample will have decayed. This is called the **half-life**.
- **Half-life is the time it takes for half of the unstable nuclei in a sample to decay or for the activity of the sample to halve or for the count rate to halve. Count-rate is the number of decays recorded each second by a detector, such as the Geiger-Muller tube.**



The illustration above shows how a radioactive sample is decaying over time.

Nuclear equations

- A nucleus changes into a new element by emitting **alpha particles** or **beta particles**. These changes are described using nuclear equations.
- Alpha decay (two **protons** and two **neutrons**) changes the **mass number** of the element by -4 and the **atomic number** by -2. An alpha particle is the same as a helium-4 **nucleus**.

Nuclear Equations

Example: $^{219}_{86}Rn \rightarrow ^{215}_{84}Po + ^{4}_{2}He$

- Beta decay changes the atomic number by +1 (the nucleus gains a proton) but the mass number remains unchanged (it gains a proton but loses a neutron by ejecting an **electron**, so a beta particle is an electron).

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

- **Gamma** is pure energy and will not change the structure of the nucleus in any way.

Irradiation

- Shining visible **radiation** from a torch beam onto a hand lights the hand up because the hand has been exposed to light.
- Exposing objects to beams of radiation is called **irradiation**. The term applies to all types of radiation including radiation from the **nuclei** of **atoms**.
- Irradiation from **radioactive decay** can damage living cells. This can be put to good use as well as being a hazard.

Irradiation for sterilisation:

- Irradiation can be used to preserve fruit sold in supermarkets by exposing the fruit to a **radioactive** source - typically cobalt-60.
- The **gamma rays** emitted by the cobalt will destroy any bacteria on the fruit but will not change the fruit in any significant way.
- The process of irradiation does not cause the irradiated object to become radioactive.

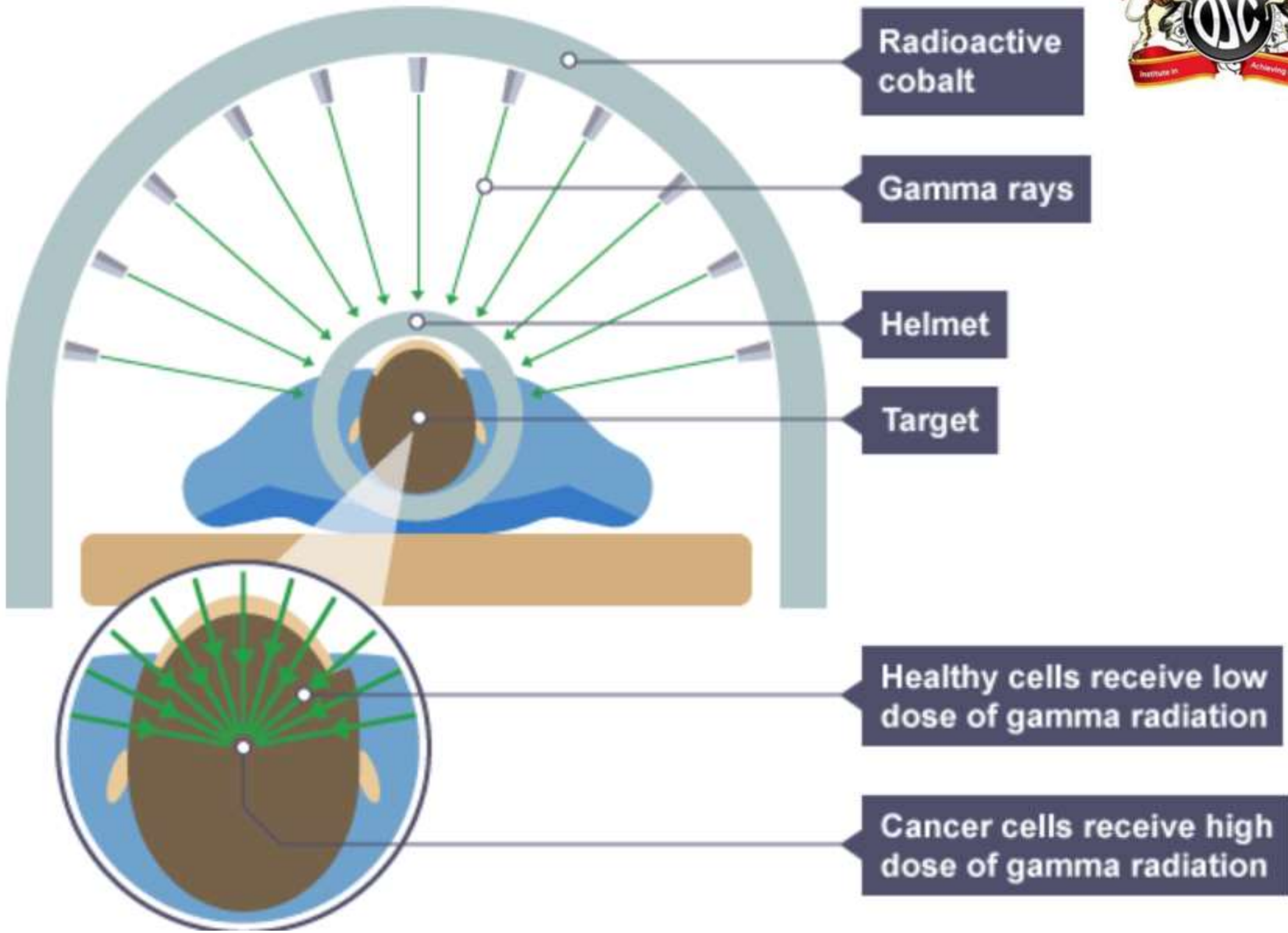
Medical irradiation

Doctors also use radioactive sources for a number of reasons.

For example:

- **sterilisation** of surgical instruments
- beams of gamma rays, called a gamma knife, can be used to kill cancerous tumours deep inside the body

- These beams are aimed at the tumour from many different directions to maximise the dose on the tumour but to minimise the dose on the surrounding soft tissue. This technique can damage healthy tissue, so careful calculations are done to establish the best dose - enough to kill the tumour, but not so much so that the healthy tissue is damaged.



Radioactive cobalt
Gamma rays
Helmet
Target
Healthy cells receive low dose of gamma radiation
Cancer cells receive high dose of gamma radiation

Medical Irradiation

- In medical applications that involve using radioactive sources, efforts are made to ensure that irradiation does not cause any long-term effects. This is done by considering:
- the nature of decay (**alpha**, **beta** or **gamma**)
- the **half-life** (long enough for the isotope to produce useful measurements, but short enough for the radioactive sources to decay to safe levels soon after use)
- **toxicity**
- If the half-life chosen is too long, the damaging effects of the radiation would last for too long and the dose received would continue to rise.

Irradiation

Advantages

- sterilisation can be done without high temperatures
- it can be used to kill bacteria on things that would melt

Disadvantages

- it may not kill all bacteria on an object
- it can be very harmful - standing in the environment where objects are being treated by irradiation could expose people's cells to damage and **mutation**

Contamination

- Contamination occurs if an object has a radioactive material introduced into it.
- An apple exposed to the **radiation** from cobalt-60 is irradiated but an apple with cobalt-60 injected into it is **contaminated**.
- As with **irradiation**, contamination can be very useful as well as being potentially harmful.

Medical contamination

- In some cases, injected radioactive sources (such as technetium-99) can be used as **tracers** to make soft tissues, such as blood vessels or the kidneys, show up through medical imaging processes. An **isotope** emits **gamma rays** that easily pass through the body to a detector outside the body, for example an x-ray machine or a 'gamma camera'. In this way, the radioactive isotope can be followed as it flows through a particular process in the body.
- Changes in the amount of gamma **emitted** from different parts would indicate how well the isotopes are flowing, or if there is a blockage.

- In medical applications that involve injecting radioactive sources, efforts are made to ensure that contamination does not cause any long-term effects. This is done by choosing isotopes that:
- have very short **half-lives** - sources used typically have half-lives of hours so after a couple of days there will hardly be any radioactive material left in a person's body
- are not poisonous

Contamination

Advantages

- Radioactive isotopes can be used as medical and industrial tracers
- Use of isotopes with a short half-life means exposure can be limited
- Imaging processes can replace some invasive surgical procedures

Disadvantages

- Radioactive isotopes may not go where they are wanted
- It can be difficult to ensure that the contamination is fully removed so small amounts of radioisotope may still be left behind
- Exposure to radioactive materials can potentially damage healthy cells

Irradiation

- Occurs when an object is exposed to a source of radiation outside the object
- Doesn't cause the object to become radioactive
- Can be blocked with suitable shielding
- Stops as soon as the source is removed

Contamination

- Occurs if the radioactive source is on or in the object
- A contaminated object will be radioactive for as long as the source is on or in it
- Once an object is contaminated, the radiation cannot be blocked from it
- It can be very difficult to remove all of the contamination

The effects of radiation on the human body

Eyes	High doses can cause cataracts.
Thyroid	Radioactive iodine can build up and cause cancer, particularly during growth.
Lungs	Breathing in radioisotopes can damage DNA.
Stomach	Radioactive isotopes can sit in the stomach and irradiate for a long time.
Reproductive organs	High doses can cause sterility or mutations.
Skin	Radiation can burn skin or cause cancer.
Bone marrow	Radiation can cause leukaemia and other diseases of the blood.

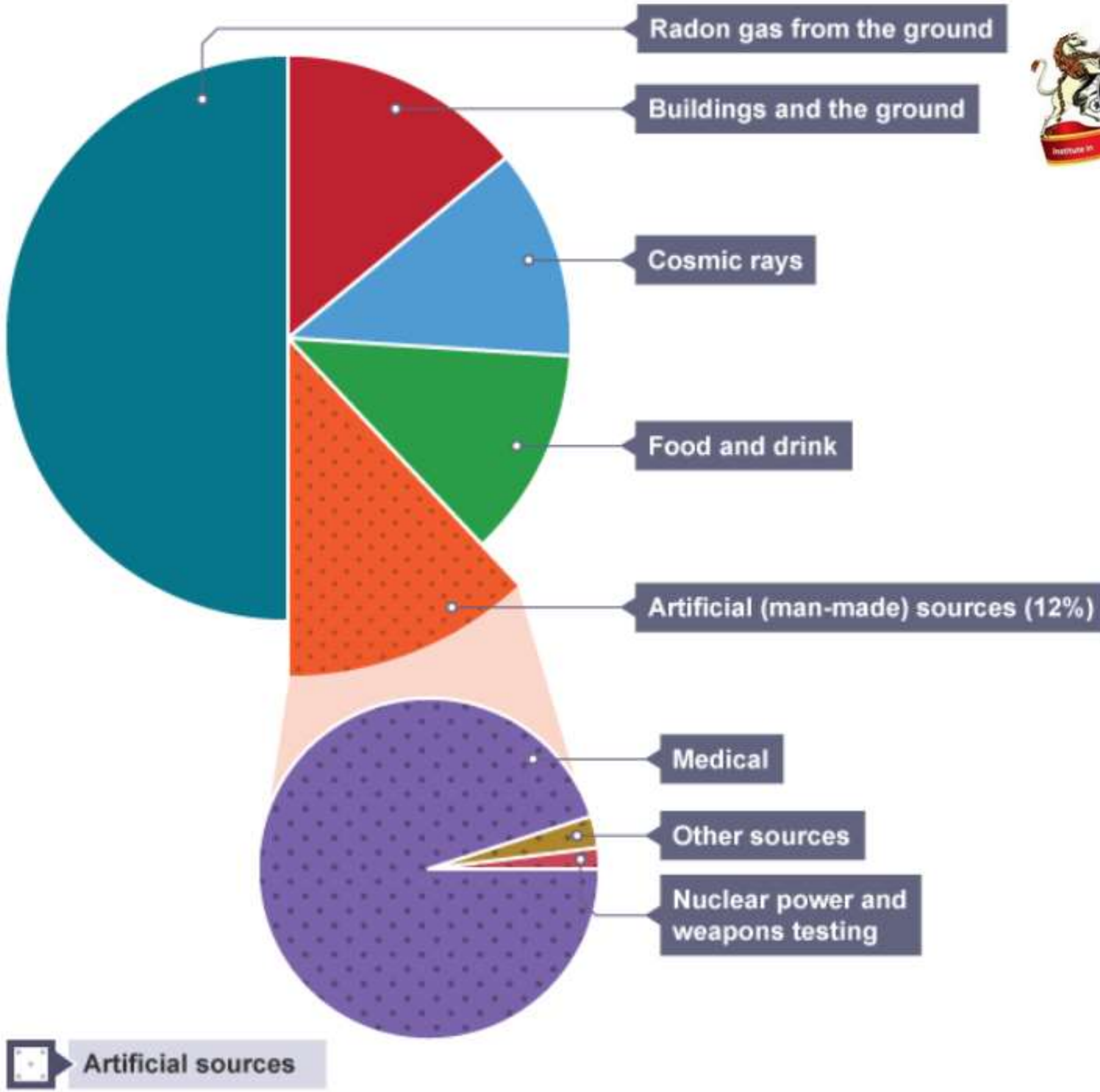
Managing the risks

Given that radioactive materials are hazardous, certain precautions can be taken to reduce the risk of using radioactive sources. These include:

- keep radioactive sources like technetium-99 shielded (preferably in a lead-lined box) when not in use
- wear protective clothing to prevent the body becoming contaminated should radioactive isotopes leak out
- avoid contact with bare skin and do not attempt to taste the sources
- wear face masks to avoid breathing in materials
- limit exposure time - so less time is spent around radioactive materials
- handle radioactive materials with **tongs** in order to keep a safer distance from sources
- monitor exposure using detector badges, etc

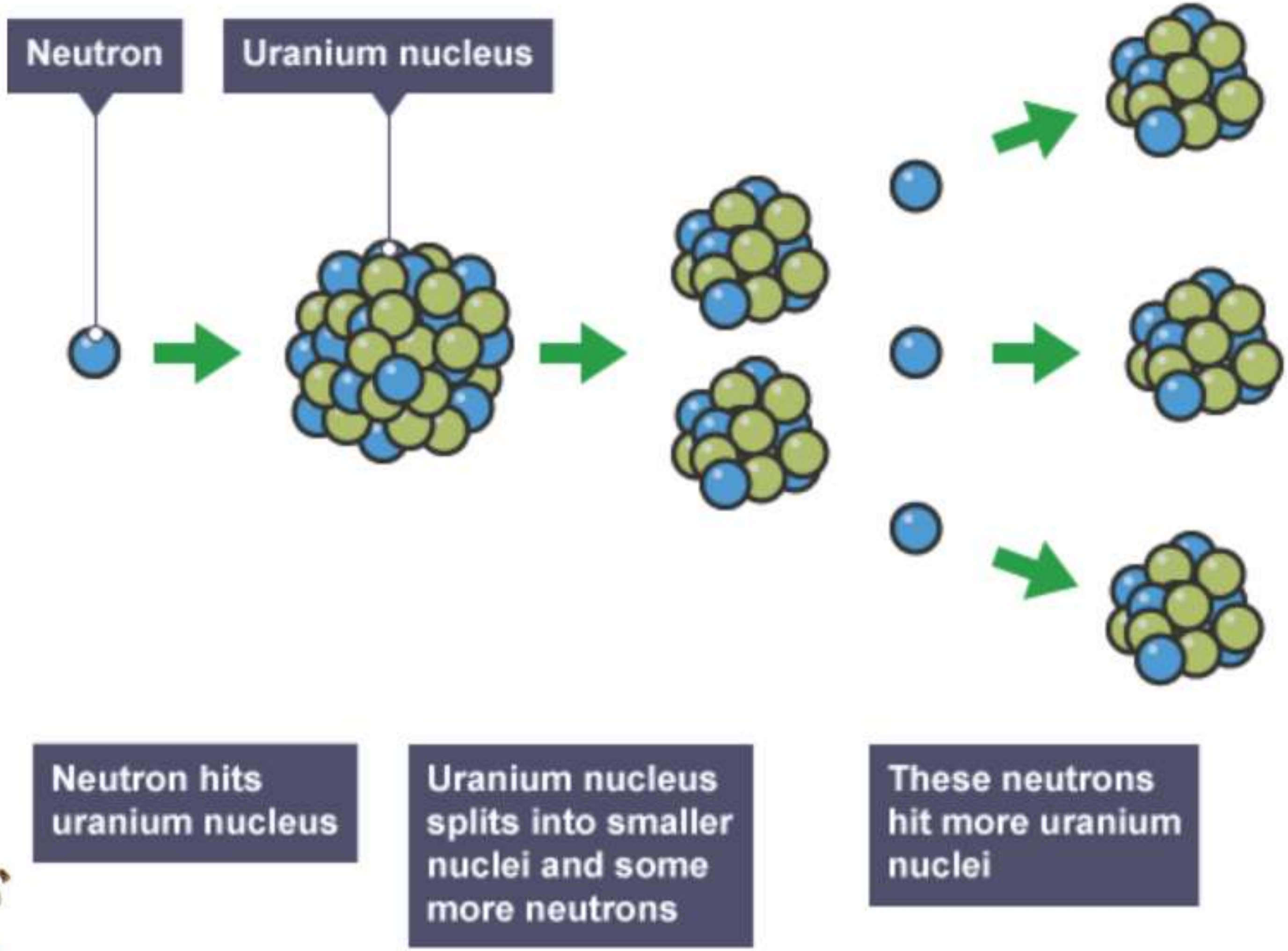
Background radiation

- **Radioactive** materials occur naturally and, as a result, everyone is exposed to a low-level of radiation every day.
- This exposure comes from a mixture of natural and man-made sources.


Radon gas from the ground
Buildings and the ground
Cosmic rays
Food and drink
Artificial (man-made) sources (12%)
Medical
Other sources
Nuclear power and weapons testing
Artificial sources

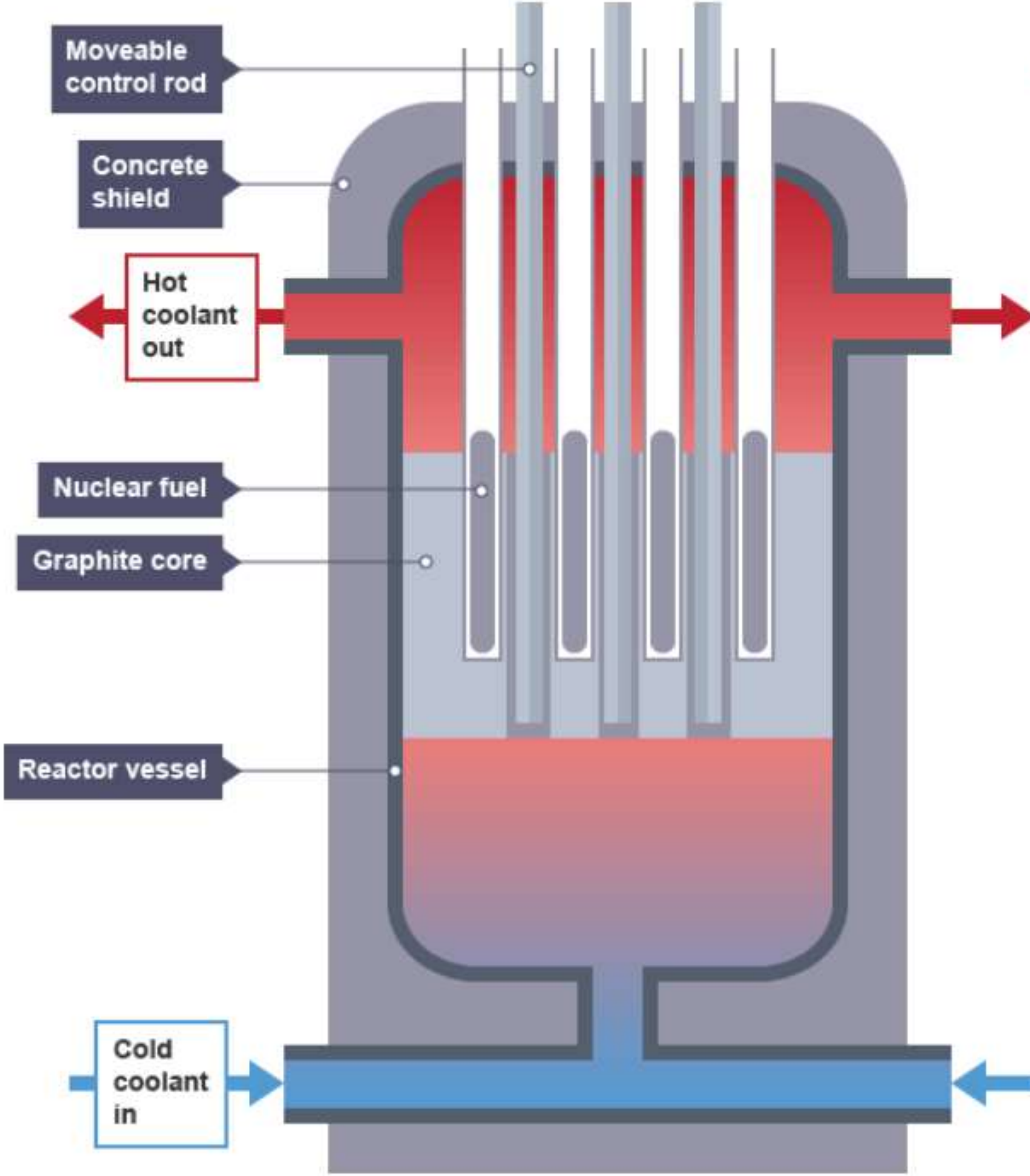
Nuclear fission

- **Nuclear fission** is the splitting of a large atomic nucleus into smaller nuclei.



Fission reactors:

- A fission reactor contains a number of different parts:
- **nuclear fuel** (the uranium **isotope** that will split when triggered by an incoming **neutron**) - the fuel is held in rods so that the neutrons released will fly out and cause **nuclear fission** in other rods
- **graphite core** - graphite slows the neutrons down so that they are more likely to be absorbed into a nearby fuel rod
- **control rods** - these are raised and lowered to stop neutrons from travelling between fuel rods and therefore change the speed of the **chain reaction**
- **coolant** - this is heated up by the energy released from the fission reactions and is used to boil water to drive **turbines** in the power station
- concrete shield - the daughter products of the fission reaction are **radioactive** and can be a **hazard**

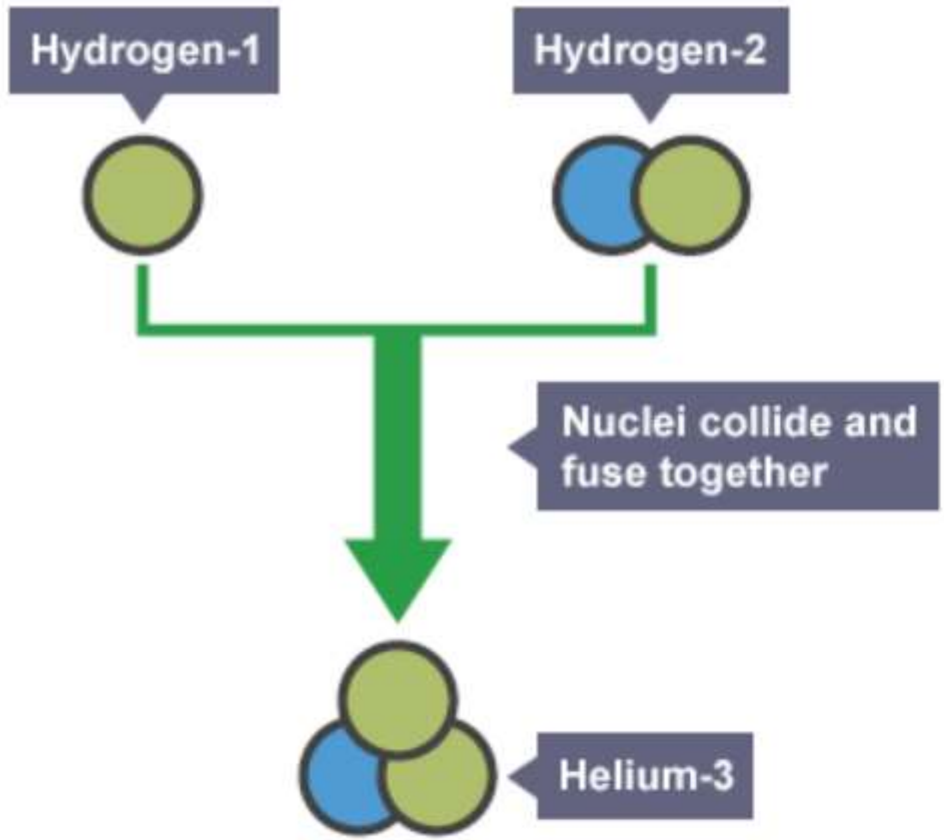


Moveable control rod
Concrete shield
Hot coolant out
Nuclear fuel
Graphite core
Reactor vessel
Cold coolant in

Nuclear fusion

- **Nuclear fusion** is when two small, light **nuclei** join together to make one heavy nucleus. Fusion reactions occur in stars where two hydrogen nuclei fuse together under high temperatures and pressure to form a nucleus of a helium **isotope**.
- There are a number of different nuclear fusion reactions happening in the Sun. The simplest is when four hydrogen nuclei become one helium nuclei.

$$4\,{}_{1}^{1}H \rightarrow {}_{2}^{4}He$$


Hydrogen-1
Hydrogen-2
Nuclei collide and fuse together
Helium-3