



AQA GCSE Physics Atomic Structure

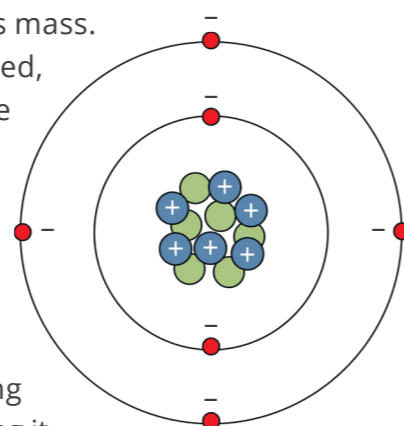
Knowledge Organiser



Atomic Structure

Atoms contain a central **nucleus** which makes up most of its mass. The nucleus contains **protons**, which are positively charged, and **neutrons**, which have no charge. This means that the nucleus is positively charged overall.

Surrounding the nucleus are shells containing negatively charged **electrons**. Electrons are found at specific distances from the nucleus. An electron found closer to the nucleus is said to be at a lower **energy level** than an electron further away. Electrons can move closer to the nucleus by emitting **electromagnetic radiation** or move further away by absorbing it.



The radius of an atom is in the order of 1×10^{-10} m.

The radius of an atomic nucleus is around $\frac{1}{10\,000}$ of the atomic radius.

Atomic Number and Mass Number

The **atomic number** is the number of protons in the nucleus of an atom of an element. Because atoms have no overall charge, the number of protons and electrons in each atom is equal. Atoms of the same element have the same number of protons.

12	—	mass number
C	—	element symbol
carbon	—	element name
6	—	atomic number

The nucleus contains most of the mass of the atom. The **mass number** is the total number of protons and neutrons in the nucleus of an atom. The mass number is always bigger than the atomic number. You can find the number of neutrons in an atom by subtracting the atomic number from the mass number.

Isotopes

Atoms of the same element have the same number of protons. **Isotopes** are atoms of the same element with different numbers of **neutrons**. This means that they will have the same atomic number but different mass numbers.

12	—	different	14
C	—	mass number	C
carbon	—	same	carbon
6	—	atomic number	6

Isotope	Atomic Number	Mass Number	Protons	Neutrons	Electrons
carbon-12	6	12	6	6	6
carbon-13	6	13	6	7	6
carbon-14	6	14	6	8	6

Controlling Fission

If fission reactions are not controlled, **chain reactions** can occur. This is where fission neutrons continue to be made and are then absorbed by more fissionable nuclei, leading to huge amounts of energy being released. Uncontrolled chain reactions are the principle behind nuclear weapons.

All the products of fission reactions have a large kinetic energy store. Different parts of a nuclear power station are designed to slow down fission reactions and increase safety.

Control rods

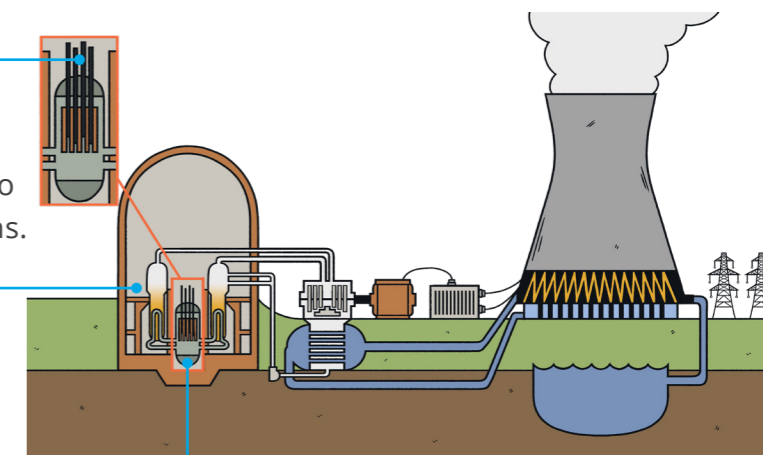
These absorb fission neutrons. They can be lowered into and raised out of the reactor vessel to control the rate of chain reactions.

Containment building

This surrounds the nuclear reactor with a thick concrete wall, preventing irradiation of the surroundings.

Reactor vessel

This contains enriched uranium fuel. It is made of thick steel to withstand the high temperature and pressure reached during fission reactions. It also contains water, which acts as a moderator and a coolant, slowing down neutrons before they collide with uranium nuclei. This increases the rate of fission because neutrons that collide with nuclei too quickly are reflected rather than absorbed.



Nuclear Fusion

Nuclear fusion is where two light nuclei join to form a heavier nucleus. Some of the mass of the smaller nuclei is converted to the energy of radiation in this process. Nuclear fusion occurs in the Sun and other stars, where hydrogen nuclei fuse to form helium and heavier elements.

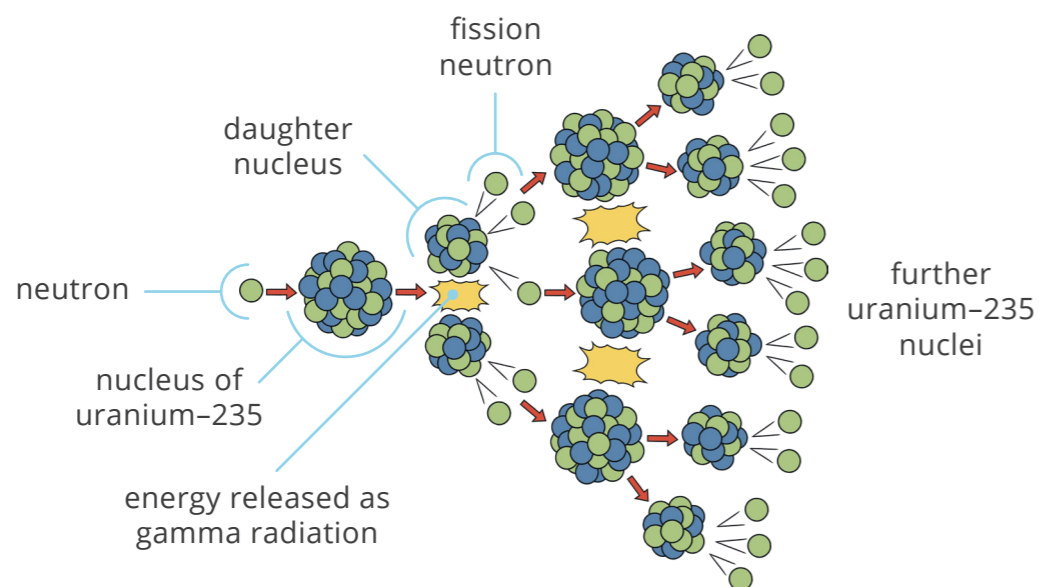
Nuclear fusion must occur at a high temperature because a lot of energy is required to overcome the electrostatic repulsion experienced between the protons of different nuclei. High-strength magnets would also need to be used to hold the nuclei together. The cost, energy demands and safety concerns around this process mean that nuclear fusion is not currently commercially possible.

Nuclear fusion is seen as the future of 'clean' energy production because it only produces helium gas, which is not harmful to the environment.

Nuclear Fission

Inside nuclear power stations, large, unstable nuclei are split into smaller, more stable nuclei by firing **neutrons** at them. As they split, the nuclei release large amounts of energy in the form of **gamma radiation**. This process is known as **nuclear fission** and it changes mass into energy.

The fuel for nuclear fission is usually enriched uranium. This contains 2-3% of the isotope uranium-235 which can undergo fission. The rest of the uranium atoms are uranium-238 which do not undergo fission. In nature, a sample of uranium would only typically contain less than 1% of the fissionable isotope.



Nuclear fission typically has the following stages:

A slow-moving **neutron** is fired at a nucleus of **uranium-235**.

The neutron is absorbed into the uranium-235 nucleus. It becomes uranium-236 which is very **unstable**.

The unstable nucleus splits into two similarly sized **daughter nuclei**. This releases a large amount of energy in the form of gamma radiation.

Two or three neutrons are also released. These are called **fission neutrons** and have a large kinetic energy store.

The fission neutrons can go on to collide with more uranium-235 nuclei, repeating the process. This is known as a **chain reaction**.

Sometimes nuclear fission can occur naturally, without the need for the nucleus to absorb a neutron. This is known as **spontaneous fission** and is very rare.

Changing the Number of Subatomic Particles

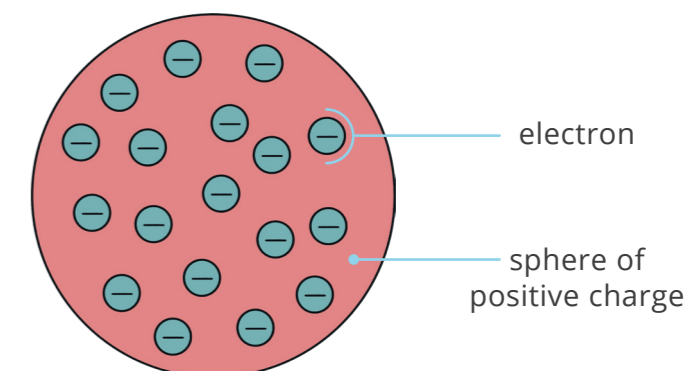
- Changing the number of **protons** creates a different **element**. The **atomic number** changes.
- Changing the number of **neutrons** creates a different **isotope**. The **mass number** changes.
- Changing the number of **electrons** creates an **ion**. When electrons are **gained**, the ion has a **negative** charge. When electrons are **lost**, the ion has a positive charge.

Development of the Model of the Atom

The development of the **nuclear model** of atomic structure is an example of a scientific model changing over time because of developing experimental evidence.

Atoms were originally thought to be tiny spheres which could not be divided into smaller parts.

The electron was discovered. This led to the development of the **plum pudding model** of the atom by JJ Thomson in 1897. This suggested that an atom was a ball of positive charge with negative electrons distributed throughout it.

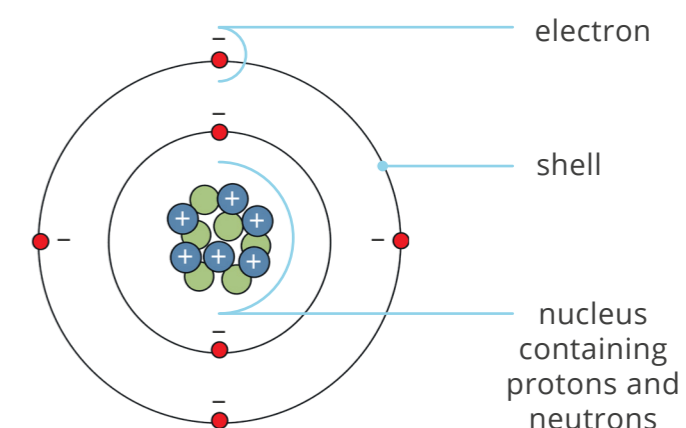


Ernest Rutherford's 1909 **alpha particle scattering experiment** showed that the mass of the atom was concentrated in its centre, which was charged. The centre was called the nucleus. The plum pudding model was replaced by the **nuclear model**.

Based on the 1913 theory of Niels Bohr, the nuclear model was adapted to add electrons orbiting the nucleus at specific distances.

Experiments showed that the positive charge in the nucleus could be split into smaller units of equal charge. They were called protons.

James Chadwick discovered that the neutron was found within the nucleus in 1932, about 20 years after the nuclear model was accepted.



Radioactive Decay

Small atoms are **stable** if they have a similar number of protons and neutrons in their nucleus. If atoms have too many, or too few neutrons they become **unstable**.

Unstable atoms emit **radiation** to become more stable. This is called **radioactive decay** and is an entirely **random** process. Unstable atoms emit radiation until they become stable and are no longer radioactive. The rate at which a source of unstable nuclei decays is known as its **activity** and is measured in **becquerel (Bq)**. Activity can be measured using a detector like a Geiger-Müller tube. The number of decays recorded each second by a detector is known as the **count-rate**.

Nuclear Radiation

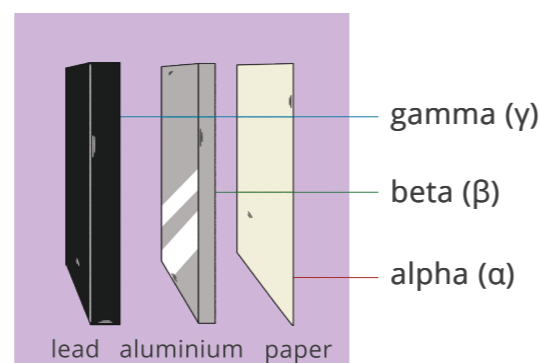
Nuclear radiation is usually emitted in one of three ways: as **alpha** particles, **beta** particles, or **gamma** rays. Sometimes a neutron may be emitted from the nucleus.

Name and Symbol	Type of Radiation	Ionising Power	Range in Air
alpha (α)	A particle made of two protons and two neutrons (a helium nucleus).	high	very short (< 5cm)
beta (β)	In the nucleus, a neutron turns into a proton and an electron. The electron is emitted from the nucleus at high speed.	low	short (\approx 1m)
gamma (γ)	An electromagnetic wave released from the nucleus.	very low	long (> 1km)

Radiation is harmful because it can damage body cells. This damage occurs when alpha or beta particles collide with atoms within body cells, or when gamma rays pass through them. The chance of radiation causing damage is known as its **ionising power**. Alpha particles have high ionising power because they are the most likely to cause damage to body cells.

The different types of radiation also have different **penetration power**. Alpha particles are the least penetrating and can be stopped by paper or skin. Beta particles can be stopped by a thin sheet of aluminium foil. Gamma rays are the most penetrating and can only be stopped by a thick layer of lead or concrete.

The properties of each type of radiation make them suitable for different purposes. For example, alpha-emitting radioactive sources are commonly used in smoke detectors. Smoke particles disrupt the stream of alpha particles causing the alarm to sound. Although alpha particles are the most ionising, they cannot pass through the casing of the alarm so are not hazardous to use.

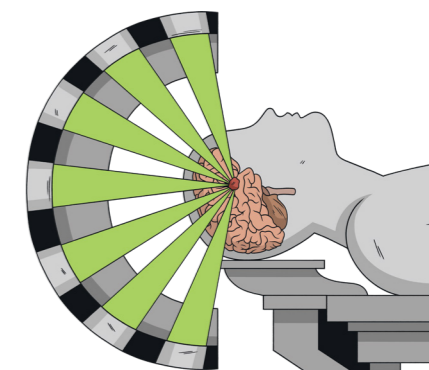


Uses of Nuclear Radiation

Radiation is used in medicine as a diagnostic tool. It can also be used to treat conditions like cancer. The type of radioactive source used needs to be effective while being as safe as possible.

Examples of uses of radiation in medicine include:

- **Radioactive tracers:** These can detect blockages and leaks, for example, in the kidney. The patient drinks water containing a small amount of a radioactive isotope whose passage through the kidney can be monitored using a detector. If the kidney is blocked, the reading increases because the radioactive isotope cannot be excreted. Radioactive iodine is usually used as it has a short half-life of eight days and emits gamma radiation, which can be detected outside of the body. It also decays into a stable product.
- **Gamma cameras:** A radioactive isotope of technetium is consumed by the patient. This emits gamma radiation, causing a crystal on a detector to produce flashes of light which are recorded by a camera. Over time, this builds up an image that can map the function of different parts of the body. The isotope of technetium has a half-life of around six hours, which is long enough to record the images but prevents patients from being radioactive when sent home. Gamma radiation can penetrate the skin but is the least ionising source.
- **Radiation therapy:** Multiple narrow beams of gamma radiation from a radioactive isotope of cobalt can be focused on the cells in a cancerous tumour to destroy them. Gamma radiation is used because it can penetrate through the body and poses the least risk of ionisation to healthy cells. Aiming multiple beams at different angles means the tumour receives a high dose of radiation but surrounding healthy cells receive a much lower dose.



When using a radioactive source for a medical diagnosis or treatment, medical professionals will consider the following factors:

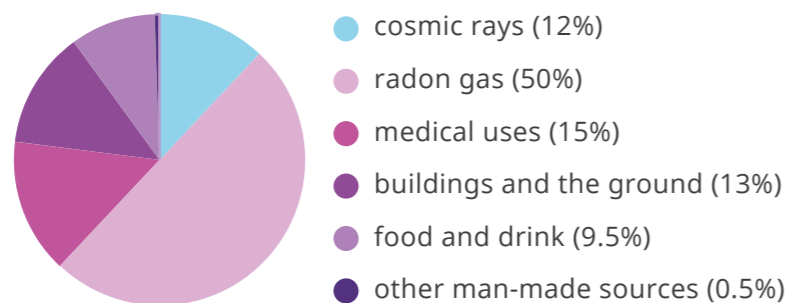
- **Half-life:** The source needs to be radioactive for long enough to be useful. However, the half-life needs to be short to reduce the length of time the patient is contaminated for. This reduces the risk of ionisation of healthy body cells.
- **Type of decay:** Radioisotopes used in medicine are usually emitters of gamma radiation. This reduces the risk of ionisation to healthy body cells. Gamma radiation is also able to penetrate body tissue allowing it to be detected by imaging equipment.
- **Decay products:** After the radioactive source has undergone decay, it needs to form products that can be safely excreted by the body in a short amount of time.
- **Efficacy:** Not all radioactive sources will work in the same way. Medical professionals will only use a treatment that has been shown to work effectively for that condition through the peer-review process.

Background Radiation

Radiation is found around us all of the time. The radiation which we are exposed to in our daily lives is called **background radiation**.

Most background radiation occurs naturally from rocks and soil in the ground, the atmosphere or from cosmic rays from outer space. A very small amount is emitted from man-made sources, such as nuclear accidents or weapons testing.

Sources of Background Radiation



The amount of background radiation you are exposed to can depend on factors such as where you live and what job you do.

Radiation Dose: A measure of the risk of harm resulting from an exposure of the body to radiation. Measured in sieverts (Sv). 1000 millisieverts (mSv) = 1 sievert (Sv)

Different Half-Lives of Radioactive Isotopes

There are more than 3000 known radioactive isotopes (also known as radioisotopes), and the majority of these are man-made. Each radioisotope has unique properties, including the length of its half-life, which makes it useful for specific purposes.

Radioisotopes used in medicine tend to have short half-lives. They are radioactive for long enough to be useful as a treatment or diagnostic tool, but decay into harmless products quickly. This reduces the risk of healthy body cells being ionised.

Radioisotope	Type of Decay	Half-Life	Use
americium-241	alpha	432 years	in smoke detectors
carbon-11	gamma	20 minutes	in medical scanning to detect tumours
carbon-14	beta	5730 years	in radiocarbon dating to determine the age of archaeological artefacts
iodine-131	beta	8 days	in the treatment of thyroid conditions
sodium-24	beta	15 hours	to study blood circulation
strontium-90	beta	29 years	to inspect helicopter blades for cracks
technetium-99m	gamma	6 hours	as a radioactive tracer using a gamma camera
uranium-235	alpha	704 million years	as the fuel for nuclear fission

Nuclear Equations

A nuclear equation is used to represent radioactive decay. It shows the atomic and mass numbers of the parent and daughter nuclei.

Alpha Decay

When an unstable nucleus undergoes alpha decay, its **atomic number decreases by two** and its **mass number decreases by four**. This is due to the emission of an alpha particle from the nucleus. The following equation shows the alpha decay of radium-226.



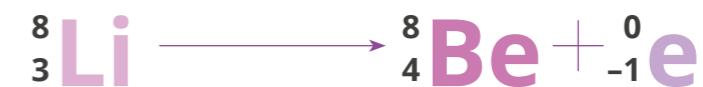
Radium-226 is the parent nucleus. It is unstable and undergoes alpha decay.

Radon-222 is the daughter nucleus which is produced when radium-226 loses two protons and two neutrons as an alpha particle.

Alpha particles are represented by the symbol for helium because they are made of two protons and two neutrons, like a helium nucleus.

Beta Decay

When an unstable nucleus undergoes beta decay, its **atomic number increases by one**, however, its **mass number stays the same**. This is because a neutron turns into a proton and an electron. The proton remains in the nucleus, but the electron is emitted as a particle of beta radiation. The following equation shows the beta decay of lithium-8.



Lithium-8 is the parent nucleus. It is unstable and undergoes beta decay.

Beryllium-8 is the daughter nucleus produced when a neutron in the nucleus of lithium-8 turns into a proton.

Beta particles are a single, high-speed electron. They are represented by the symbol 'e'. They have no mass and a negative charge of -1.

Gamma Decay

Gamma radiation is emitted as an electromagnetic wave. This means that it does not cause the atomic number, mass number or the charge of the nucleus to change.

Type of Decay	Effect on Atomic Number	Effect on Mass Number	Reason
alpha (α)	decreases by two	decreases by four	Two protons and two neutrons are released from the nucleus.
beta (β)	increases by one	no change	A neutron changes into a proton. An electron is released.
gamma (γ)	no change	no change	Gamma radiation is an electromagnetic wave.

Half-Life

Radioactive decay is **random**. It is not possible to know which nuclei in a sample of radioactive isotopes will decay or when they will do so. Instead of predicting when individual nuclei will decay, the time it takes for half of the sample to decay is measured. The time it takes the number of nuclei in a sample of radioactive isotopes to halve is known as its **half-life**.

Half-life: The time it takes for the number of nuclei of a radioactive isotope in a sample to halve, or the time it takes for the count-rate (or activity) from a sample containing the isotope to fall to half its initial level.

The half-life of a radioactive sample can be found using a graph showing the activity, count-rate, or mass of the sample over time. The steps below describe how to do this.

1. Read the original activity, count-rate or mass of the sample from the graph.

On the graph, the initial activity of the sample is 80Bq.

2. Calculate half of this initial value.

$$80 \div 2 = 40\text{Bq}$$

3. Draw a straight line across from your calculated value until it touches the graph.

4. At this point, draw a straight line down through the x-axis. The point where your line crosses the x-axis is the half-life of the sample.

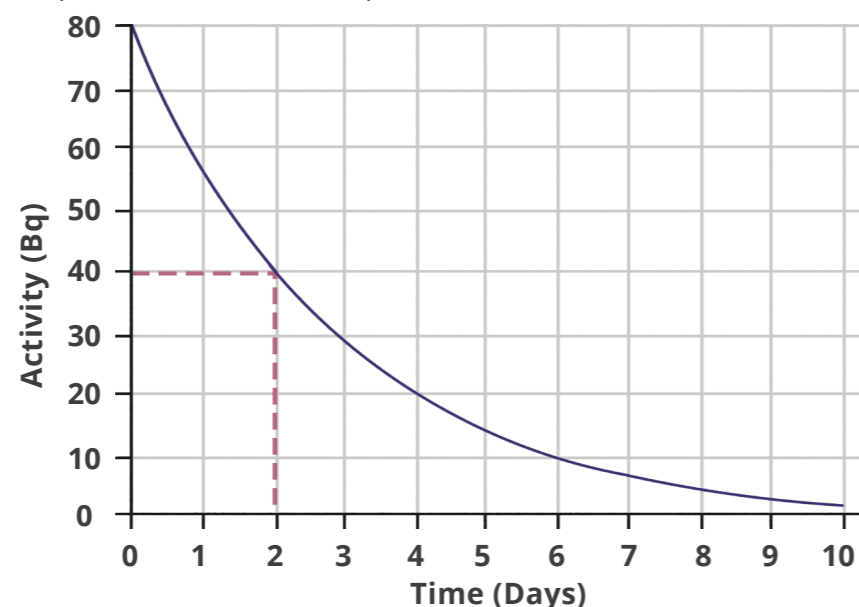
In this example, the half-life is **two days**. You can check this where two days later, at day four, the activity has halved again to 20Bq. By day six three half-lives have passed; the activity has halved again to 10Bq.

The fraction of a sample remaining after n half-lives can be calculated as: $\frac{1}{2^n}$

Calculating net decline (higher tier only):

You should be able to express the net decline of a radioactive emission after a given number of half-lives as a ratio. To do this, you divide the count-rate or activity after n half-lives by the original count-rate or activity.

In the graph above, the net decline after three half-lives can be calculated as: $10 \div 80 = \frac{1}{8}$. This can also be written as 0.125.



Radioactive Contamination

When living cells are exposed to radiation, they can become damaged. Mutations in the DNA in cells can cause cancer. Exposure to a radioactive source can be a result of irradiation or **radioactive contamination**.

Irradiation: The process of exposing an object to nuclear radiation. It does not become radioactive itself.

The risk of damage to living cells as a result of irradiation can be reduced in three ways.

- **Shielding:** Scientists use equipment such as lead-lined aprons to protect themselves from irradiation by gamma sources. They may also stand behind thick concrete walls when a radioactive source is in use. When not in use, the source is stored in a lead-lined box.
- **Distance:** Increasing the distance between the body and the radioactive source reduces the risk of irradiation.
- **Time:** Being exposed to the source for as little time as possible provides less opportunity for ionisation to occur.

Irradiation can also be useful. For example, it can be used to sterilise medical equipment by destroying harmful bacteria on its surface.

Radioactive Contamination: The unwanted presence of materials containing radioactive atoms on other materials.

A contaminated object becomes radioactive itself for as long as it contains radioactive material. This is difficult to remove. Sometimes radioactive contamination can be useful, for example, in diagnostic medicine. When using radioactive sources **inside** the body, the risk of damage to healthy cells can be minimised by:

- using a source with a **short half-life**. This minimises the risk of damage to healthy body cells by limiting the time they are exposed to ionising radiation.
- using a **gamma-emitting source**. Gamma radiation has lower ionising power than alpha and beta sources so is less likely to damage healthy cells. It is also the only type that can penetrate the skin barrier and be detected by diagnostic machines.

Sources that are used **outside** the body, for example in fire alarms, need to have a low range and penetrating power. Alpha and beta-emitting sources can be more safely used in these situations provided they are encased securely.

Scientists study the beneficial and harmful effects of different types of radiation on humans. The findings of these studies are published and undergo the process of **peer review**. This is where scientists working in the same field check the findings for accuracy. This prevents false or misleading information from becoming accepted as true by the wider public.

Studies are also checked for **reproducibility**. This is where the same method can be repeated by a different set of scientists and get the same results. By ensuring that findings are valid, new knowledge is added to a scientific field and further developments can be made. It also helps to keep both patients and medical professionals as safe as possible when using radioactive sources.