Nuclear Physics

The structure of the atom and the nucleus, nuclide notation and isotopes, detecting radioactivity and background radiation, alpha, beta and gamma radiation, decay equations, fission and fusion, half-life and its uses, and safety with radioactive materials.

5.1.1 The atom

An atom has a tiny, dense, positively charged **nucleus** at its centre. **Electrons** (negatively charged) orbit the nucleus.

Particle	Relative charge	Relative mass
proton	$+1$	1
neutron	0	1
electron	-1	about $\frac{1}{2000}$ (very small)

A neutral atom has equal numbers of protons and electrons, so the charges cancel.

The alpha-particle scattering experiment

In this experiment, a beam of alpha particles (positive) was fired at a very thin sheet of gold foil, and a detector was moved round to count the particles at different angles.

Observation	What it shows
most alpha particles went straight through	an atom is **mostly empty space**
a few were deflected through large angles, and a very few bounced almost straight back	the **nucleus is very small** and holds a concentrated mass
the particles that were deflected were repelled	the nucleus is **positively charged** (it repels positive alpha particles)

So the experiment provides evidence for a very small nucleus surrounded by mostly empty space, a nucleus that contains most of the mass of the atom, and a nucleus that is positively charged.

5.1.2 The nucleus

The nucleus is made of **protons** and **neutrons**, which are together called **nucleons**.

An atom becomes an **ion** when it gains or loses electrons:

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- losing electrons gives a **positive ion** (more protons than electrons);
- gaining electrons gives a **negative ion**.

> **Proton number (atomic number) Z is the number of protons in the nucleus. Nucleon number (mass number) A is the number of protons plus neutrons. So the number of neutrons is $A - Z$.**

A **nuclide** is a particular type of nucleus. It is written in **nuclide notation**: ${}^{A}_{Z}\mathrm{X}$, where X is the chemical symbol.

> **TRY IT**
>
> Carbon-14 is written ${}^{14}_{6}\mathrm{C}$. How many protons, neutrons and (in a neutral atom) electrons does it have?

- Protons: $Z = 6$.
- Neutrons: $A - Z = 14 - 6 = 8$.
- Electrons in a neutral atom: 6.

> **TRY IT**
>
> How many neutrons are in ${}^{235}_{92}\mathrm{U}$?

$235 - 92 = 143$

Isotopes are atoms of the same element (the same Z) with **different numbers of neutrons** (different A). They have the same chemical properties. Carbon-12 and carbon-14 are isotopes of carbon: both have 6 protons, but they have 6 and 8 neutrons. An element can have more than one isotope.

5.2.1 Detection of radioactivity

- **Alpha particles** can be detected with a cloud chamber (they leave visible tracks) or a spark counter.
- **Beta particles and gamma radiation** are detected with a **Geiger–Müller (GM) tube** connected to a counter.

The counter gives the **count rate**, measured in counts per second or counts per minute.

Background radiation

Background radiation is the low level of radiation that is always present. The main sources are:

- **radon gas** in the air (from rocks),

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- **rocks and buildings**,
- **food and drink**,
- **cosmic rays** from space.

To measure only a source, first measure the count rate with no source present (the background), then with the source, and subtract.

> corrected count rate = measured count rate − background count rate

> **TRY IT**
>
> With a source in place, a GM tube counts 85 counts per minute. The background count is 15 counts per minute. Find the corrected count rate.

$85 - 15 = 70$ counts per minute

5.2.2 The three types of emission

Some nuclei are **unstable** and give out radiation to become more stable. The emission is **spontaneous** (it is not caused by anything outside the nucleus) and **random** (we cannot tell when a particular nucleus will decay, or in which direction the radiation will go).

	Alpha (α)	**Beta (β)**	**Gamma (γ)**
what it is	two protons and two neutrons (a helium nucleus)	a high-speed electron from the nucleus	high-frequency electromagnetic wave
charge	$+2$	-1	none
ionising effect	strongest	medium	weakest
penetrating power	stopped by paper or a few centimetres of air	stopped by a few millimetres of aluminium	reduced by thick lead or concrete

> **NOTE**
>
> The more ionising a radiation is, the less penetrating it is. Alpha particles lose their energy very quickly by ionising the air, so they do not travel far.

Deflection in fields.

- In an **electric field**, alpha particles are deflected slightly towards the negative plate, beta particles are deflected more (they are much lighter) towards the positive plate, and gamma rays are not deflected

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because they have no charge.

- In a **magnetic field**, alpha and beta are deflected in **opposite** directions (they have opposite charges, and you can find the direction with Fleming's left-hand rule), and gamma rays are not deflected.

5.2.3 Radioactive decay

Radioactive decay is a change in an unstable nucleus that can give out α-particles or β-particles, and/or γ-radiation. It is **spontaneous** and **random**.

Decay equations. In an equation, the total of the nucleon numbers (top) and the total of the proton numbers (bottom) must each be the same on both sides.

- **Alpha decay.** The nucleus loses 2 protons and 2 neutrons. A decreases by 4 and Z decreases by 2.

$$^{241}_{95}\mathrm{Am} \rightarrow {}^{237}_{93}\mathrm{Np} + {}^{4}_{2}\alpha$$

- **Beta decay.** A neutron in the nucleus changes into a proton and an electron, and the electron is emitted. A stays the same and Z increases by 1.

$$^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\beta$$

- **Gamma emission.** A nucleus that has just emitted an alpha or beta particle often has extra energy, and gets rid of it as gamma radiation. A and Z do not change.

> **TRY IT**
>
> Radium-226 ($^{226}_{88}\mathrm{Ra}$) emits an alpha particle. Write the decay equation.

The daughter nucleus has nucleon number $226 - 4 = 222$ and proton number $88 - 2 = 86$, which is radon (Rn):

$$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\alpha$$

5.2.4 Fission and fusion

Fusion

Fusion is the joining of two small nuclei to make a larger nucleus, releasing energy. It needs very high temperatures and pressures, because the nuclei repel each other. Fusion is the energy source for stars: the Sun fuses hydrogen into helium.

Fission

Fission is the splitting of a large nucleus. A uranium-235 nucleus absorbs a neutron and splits into two smaller **daughter nuclei**, plus two or more neutrons, and releases energy.

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Chain reaction. The neutrons given out can be absorbed by other uranium-235 nuclei and make them split too. If each fission leads to more than one further fission, the reaction grows rapidly and can run out of control, as in a nuclear bomb.

In a nuclear reactor the chain reaction is controlled:

Part	Job
fuel rods	contain the uranium-235
moderator (graphite or water)	slows the neutrons down so they are more likely to cause fission
control rods (boron or cadmium)	absorb neutrons; lowering them into the reactor slows the reaction, and raising them speeds it up
coolant (water or carbon dioxide)	carries away the thermal energy to a boiler to make steam, which drives the turbine and generator

5.2.5 Half-life

The half-life of an isotope is the time taken for half the nuclei of that isotope in any sample to decay. The count rate from the sample also halves in one half-life.

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A radioactive source has a count rate (corrected for background) of 800 counts per minute. Its half-life is 3.0 hours. What is the count rate after 9.0 hours?

9.0 hours is $\frac{9.0}{3.0} = 3$ half-lives, so the count rate is halved three times:

$$800 \rightarrow 400 \rightarrow 200 \rightarrow 100 \text{ counts per minute}$$

NOTE

Subtract the background count rate **before** working out the half-lives. A decay curve is a curve that falls steeply and then flattens. To find the half-life from the curve, read the time for the count rate to fall from any value to half that value, and check with another pair of values.

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A sample has a mass of 80 g of an isotope with a half-life of 4 days. How much of the isotope is left after 12 days?

12 days is 3 half-lives: $80 \rightarrow 40 \rightarrow 20 \rightarrow 10$, so 10 g is left.

Carbon dating

Living things take in carbon, including a small constant fraction of radioactive carbon-14. When a living thing dies, no more carbon-14 is taken in, and what is there decays with a half-life of about 5700 years. Measuring the activity of carbon-14 in an old object and comparing it with that of living material shows how long ago it died.

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A piece of ancient wood has a carbon-14 activity that is a quarter of that of living wood. How old is it? (half-life of carbon-14 $= 5700$ years)

A quarter is two halvings, so two half-lives: $2 \times 5700 = 11\,400$ years.

Choosing an isotope for a job

The right isotope depends on the **type of radiation** it emits and its **half-life**.

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Use	Radiation chosen	Why
smoke alarm	alpha (americium-241)	alpha ionises the air in a small chamber so a small current flows; smoke absorbs the alpha particles and the current falls, setting off the alarm. Alpha is safe because it cannot leave the alarm. A long half-life means it lasts for years
irradiating food	gamma	gamma is penetrating and kills bacteria all through the food, and does not make the food radioactive
sterilising medical equipment	gamma	it can sterilise instruments after they have been sealed in packaging
measuring and controlling the thickness of paper or metal foil	beta (for thin paper or foil) or gamma (for thick metal)	a source on one side, a detector on the other; if the material is too thick, fewer particles get through and the count falls, so the rollers are adjusted. The radiation must be partly, not wholly, absorbed, so the thinner the material, the less penetrating the radiation chosen. Alpha would be fully stopped
diagnosing and treating cancer	gamma	gamma passes out of the body to be detected (diagnosis) or can be aimed at a tumour to kill the cells (treatment). A tracer used for diagnosis has a **short half-life**, so it does not stay radioactive in the body for long

5.2.6 Safety precautions

Ionising radiation can **damage or kill cells**, and **mutate** the DNA in them, which can lead to **cancer**.

Radioactive materials are moved, used and stored safely by:

- **reducing the time** of exposure (work quickly, and keep sources locked away when not in use);
- **increasing the distance** between the source and the person (use tongs or long handles, because the radiation gets weaker with distance);
- **using shielding** to absorb the radiation (lead or thick concrete walls, and sources kept in lead-lined containers).

Sources are clearly labelled, kept in locked, shielded stores, and people who work with them wear badges that record how much radiation they have received.

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