Exercise walk-through

Radioactivity ▪ 5.2

eXercise

You must be able to

- name the sources of background radiation and correct a count rate for it
- compare alpha, beta and gamma by nature, ionising effect and penetration, and explain the ionising order using charge and kinetic energy
- write and balance alpha and beta decay equations
- define half-life and use it in calculations, including a mass or a count rate
- explain how the radiation type and half-life decide which isotope is used for a job
- state the effects of ionising radiation on living things and the safety precautions

Method — Background radiation and the corrected count rate

Some radiation is always present: **radon 氡** gas in the air (usually the largest source), rocks and buildings, food and drink, and **cosmic rays 宇宙射线** from space. Radiation is measured with a detector joined to a **counter 计数器**, and the **count rate 计数率** is the counts each second or minute.
Always measure the background first, with the source removed, and subtract it:

$$\text{corrected count rate} = \text{measured count rate} - \text{background count rate}$$

Worked example 1. A detector next to a source reads 250 counts/min. With the source removed it reads 30 counts/min. Corrected: $250 - 30 = 220$ counts/min.

Method — The three radiations

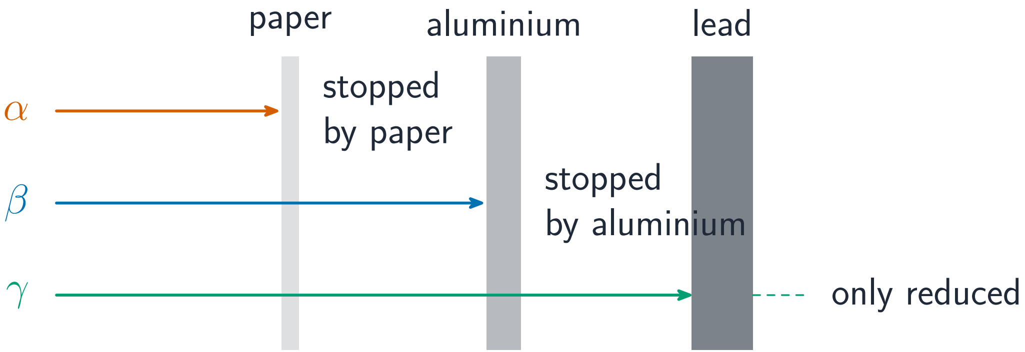
Type	What it is	Charge	Ionising	Stopped by
alpha (α)	a helium nucleus, 2 protons + 2 neutrons	$+2$	strongest	a sheet of paper, a few cm of air
beta (β)	a fast electron from the nucleus	-1	medium	a few mm of **aluminium** 铝
gamma (γ)	a high-energy electromagnetic wave	0	weakest	thick **lead** 铅 or concrete (only reduced)

Method — The three radiations

Explain the ionising order from **charge** and **kinetic energy**: an alpha particle carries a charge of $+2$ and is heavy and slow, so it passes close to many atoms and pulls strongly on their electrons, ionising a great deal and losing its energy in a short distance. A beta particle has a smaller charge (-1) and moves much faster, so it interacts with each atom for less time and ionises less. Gamma has no charge at all, so it ionises least and travels furthest.

Because alpha and beta are charged, an electric or a magnetic field deflects them in **opposite** directions, and the much lighter beta is deflected more. Gamma is not deflected.

Method — The three radiations



Alpha stopped by paper, beta by aluminium, gamma reduced by lead

Method — Decay equations

In every decay the nucleon numbers balance and the proton numbers balance.
Alpha decay loses 2 protons and 2 neutrons, so A falls by 4 and Z by 2:

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

Beta decay: inside the nucleus a neutron changes into a proton and an electron, and the electron leaves as the beta particle. So A is unchanged and Z rises by 1:

$$^{24}_{11}\text{Na} \rightarrow\ ^{24}_{12}\text{Mg} +^{\ 0}_{-1}\beta$$

Gamma emission changes neither number: the nucleus only loses energy.
Worked example 2. $^{241}_{95}$Am decays by alpha emission to an isotope of neptunium.
Nucleon number: $241 - 4 = 237$. Proton number: $95 - 2 = 93$. So

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

Method — Half-life

The **half-life** is the time for half the unstable nuclei in a sample to decay. After each half-life the number left, and the corrected count rate, falls to half. Count the halvings rather than dividing the total time.

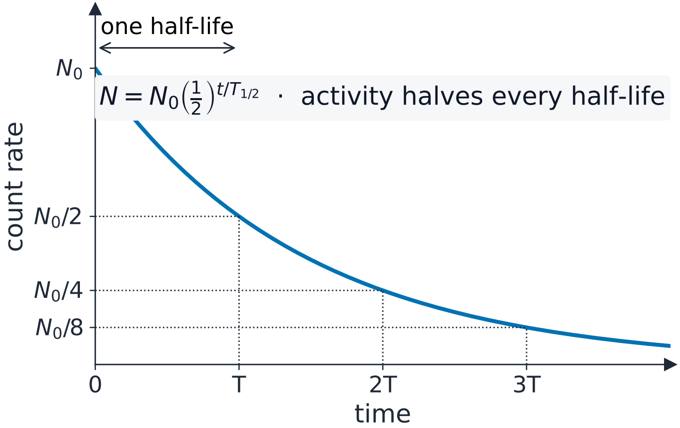
Worked example 3. A source falls from 800 to 100 counts/min and its half-life is 5 days. The halvings are $800 \to 400 \to 200 \to 100$, which is 3 half-lives, so the time is $3 \times 5 = 15$ days.

Worked example 4 (mass decayed). A source contains $25\ \mu$g of an isotope whose half-life is 29 years. Find the mass that decays in 87 years.

1. Number of half-lives: $87 \div 29 = 3$.
2. Fraction left: $\left(\frac{1}{2}\right)^3 = \frac{1}{8}$, so the mass left is $25 \div 8 = 3.1\ \mu$g.
3. The question asks for the mass that **decayed**: $25 - 3.1 = 22\ \mu$g.

Read a half-life off a graph by taking any starting value, finding half of it, and reading the time between them. Subtract the background from every reading first.

Method — Half-life



A decay curve halving each half-life

Method — Choosing an isotope, and safety

The job decides the radiation and the half-life:

- **smoke alarm**: an alpha source with a long half-life. Alpha ionises the air between two plates so a small current flows; smoke particles absorb the alpha and the current drops. Alpha is safe outside the alarm because paper (or a few centimetres of air) stops it, and the long half-life means the alarm lasts for years.
- **thickness gauge** for paper or foil: a beta source, because the amount getting through changes with the thickness (alpha would all be stopped, gamma would all pass).
- **medical tracer**: a gamma emitter with a short half-life, so the radiation escapes the body to a detector and the activity soon falls to a safe level.
- **sterilising** equipment or food, and treating tumours: gamma, because it penetrates the sealed package or the body.

Method — Choosing an isotope, and safety

Ionising radiation damages **living cells 细胞**: it can kill cells, cause **mutations 突变** in the genes, and cause cancer. To keep the **dose 剂量** low: reduce the **exposure 照射** time, increase the distance from the source, and use **shielding 屏蔽** such as lead. Handle sources with tongs, never with bare hands; point them away from people; store them in a lead-lined box.

Practice 2.1 ▪ 1 mark

State what material stops beta radiation.

Solution 2.1

Method: Choosing an isotope, and safety

Worked steps

A few millimetres of aluminium **B1**.

Practice 2.2 ▪ 2 marks

Name two sources of background radiation.

Solution 2.2

Worked steps

Any two of: radon gas in the air; rocks and buildings; food and drink; cosmic rays from space **B2**.

Practice 2.3 ▪ 2 marks

A detector reads 250 counts/min; the background is 30 counts/min. Find the corrected count rate.

Solution 2.3

Method: Background radiation and the corrected count rate

Worked steps

Corrected $= 250 - 30 = 220$ counts/min M1 A1.

Practice 2.4 ▪ 2 marks

State the nature and the charge of an alpha particle and of a beta particle.

Solution 2.4

Method: The three radiations

Worked steps

Alpha: a helium nucleus (2 protons and 2 neutrons), charge $+2$ **B1**. Beta: a fast-moving electron, charge -1 **B1**.

Practice 2.5 ▪ 2 marks

Complete this decay equation, giving both numbers for the new nucleus:
$^{210}_{84}\text{Po} \rightarrow \quad ^{?}_{?}\text{Pb} + ^{4}_{2}\alpha.$

Solution 2.5

Method: Decay equations

Worked steps

$^{206}_{82}$Pb: nucleon number $210 - 4 = 206$ **B1**, proton number $84 - 2 = 82$ **B1**.

Practice 2.6 ▪ 3 marks

A source has a half-life of 6 hours. Its corrected count rate is now 960 counts/min. Find the count rate after 18 hours.

Solution 2.6

Method: Half-life

Worked steps

$18 \div 6 = 3$ half-lives **M1**; $960 \to 480 \to 240 \to 120$ **M1**; 120 counts/min **A1**.

Practice 2.7 ▪ 4 marks

State two precautions a scientist should take when working with a radioactive source, and explain why each one lowers the dose.

Solution 2.7

Method: Choosing an isotope, and safety

Worked steps

Any two, each with its reason B4: reduce the time spent near the source, because the dose received rises with the exposure time; stand further away (use tongs), because the radiation spreads out so the intensity falls with distance; work behind lead shielding, because the lead absorbs the radiation before it reaches the body.

Exam-style 3.1 ▪ 1 mark

A source of radiation is placed near a detector. A sheet of paper between them makes no difference to the count rate, but a 5 mm sheet of aluminium reduces it almost to the background level. Which radiation is the source emitting?

A alpha only

B beta only

C gamma only

D alpha and gamma

Solution 3.1

A alpha only

B beta only ✓

C gamma only

D alpha and gamma

Worked steps

B. Paper stops alpha, so there is no alpha; aluminium stops beta and would not stop gamma, so the source emits beta only. A and D would have been blocked by the paper, and C would still pass through the aluminium.

Exam-style 3.2 ▪ 1 mark

A nucleus emits a beta particle. Which row is correct?

A nucleon number unchanged, proton number $+1$

B nucleon number unchanged, proton number -1

C nucleon number -4, proton number -2

D nucleon number -1, proton number unchanged

Solution 3.2

A nucleon number unchanged, proton number $+1$ ✓

B nucleon number unchanged, proton number -1

C nucleon number -4, proton number -2

D nucleon number -1, proton number unchanged

Worked steps

A. A neutron becomes a proton, so the proton number rises by one while the total number of nucleons is unchanged. C describes alpha decay.

Exam-style 3.3 ▪ 3 marks

A student investigates a radioactive source. Before using it she records a count rate of 24 counts/min with the source in its lead box. With the source in place the detector reads 824 counts/min.

(a) Explain why she measured the count rate before bringing out the source, and calculate the corrected count rate.

(b) The corrected count rate falls to 100 counts/min after 12 hours. Determine the half-life of the source.

(c) The source emits beta particles. Describe what happens inside a nucleus when a beta particle is emitted.

(d) Suggest, with a reason, whether this source would be suitable for a smoke alarm.

Solution 3.3

Method: Choosing an isotope, and safety

Worked steps

(a) The reading with the source shut away is the background radiation, which is always present and must be subtracted so the count rate is due to the source alone **B1** **B1**; corrected $= 824 - 24 = 800$ counts/min **A1**.

(b) $800 \to 400 \to 200 \to 100$ is 3 half-lives **M1** **M1**; half-life $= 12 \div 3 = 4$ hours **A1**.

(c) A neutron in the nucleus changes into a proton **B1** and an electron, which is emitted as the beta particle **B1**.

Solution 3.3

(d) No **B1**: beta passes through smoke without being absorbed, so the current would not change when smoke entered — an alarm needs an alpha source **B1**.

Exam-style 3.4 ▪ 3 marks

A smoke alarm contains a small americium-241 source, which decays by alpha emission to an isotope of neptunium (Np).

(a) Complete the nuclide equation: ${}^{241}_{95}\text{Am} \rightarrow \;\ldots\ldots\text{Np} + \ldots\ldots\alpha$.

(b) Describe how the alpha particles ionise the air inside the alarm.

(c) Suggest and explain two reasons why the alarm uses an alpha emitter rather than a gamma emitter.

(d) The half-life of americium-241 is 432 years. Explain why this long half-life is an advantage for a smoke alarm.

Solution 3.4

Method: Choosing an isotope, and safety

Worked steps

(a) $^{237}_{93}\mathrm{Np}$ **B1** **B1** *nucleon number, proton number* and $^{4}_{2}\alpha$ **B1**.
(b) The alpha particles are emitted from the americium **B1** and collide with (or pass close to) molecules in the air between the plates **B1**, knocking electrons out of them so the air contains ions and conducts **B1**.
(c) Any two, each with its explanation **B4**: alpha is easily absorbed by smoke particles, so the current drops as soon as smoke enters, while gamma would pass straight through and the alarm would not respond; alpha is much more ionising, so it makes the air conduct well enough to give a steady current; alpha has a very short

Solution 3.4

range and is stopped by the plastic case, so it is far less harmful to people in the house than gamma would be.

(d) The activity stays almost constant for the whole life of the alarm, so it does not need replacing **B1**.

Exam-style 3.5 ▪ 2 marks

A hospital uses a gamma-emitting isotope with a half-life of 6 hours as a medical tracer.

(a) Explain why a gamma emitter, and not an alpha emitter, is used inside the body.

(b) Explain why a half-life of 6 hours is more suitable than one of 6 years.

(c) A sample contains 80 μg of the isotope. Calculate the mass that has decayed after 24 hours.

(d) State two effects that ionising radiation can have on living cells.

Solution 3.5

Method: Choosing an isotope, and safety

Worked steps

(a) Gamma is the most penetrating, so it passes out of the body to the detector outside **B1**; alpha would be absorbed within a few centimetres of tissue, giving a large dose to the patient and no signal outside **B1**.
(b) A 6-hour half-life means the activity falls to a safe level within a day, so the patient's dose is small **B1**; a 6-year half-life would keep irradiating the patient long after the scan **B1**.
(c) $24 \div 6 = 4$ half-lives **M1**; mass left $= 80 \div 2^4 = 80 \div 16 = 5.0\ \mu g$ **M1**; mass

Solution 3.5

decayed $= 80 - 5.0 = 75\ \mu$g **A1**.

(d) Any two of: cell death; mutation of the genes; cancer **B2**.