

ESAT

Physics

Radioactivity

Free lesson notes

Covers	P7.1 to P7.4
Format	Lesson, worked examples, self-check
Price	Free

About this lesson

Some atoms are unstable. Their nuclei spontaneously change, firing out a particle or a burst of energy and turning into a different nucleus. This is **radioactive decay**, and the particles and rays it releases are called **ionising radiation**. It was discovered by accident, in 1896, when a photographic plate left near some uranium salts turned black, and today it powers smoke alarms, dates ancient wood, treats cancer, and warms the interior of the Earth.

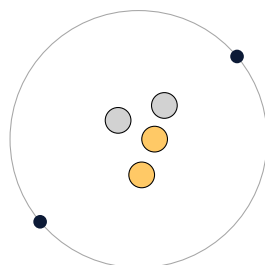
The topic is compact, and ESAT questions on it are very learnable. You need to be able to read nuclide notation and count particles, to recall the properties of the three radiations (alpha, beta, gamma), to write nuclear equations that balance, and to use half-life, the one idea that turns randomness into something you can calculate. We start with the structure of the atom, and build everything from there.

How to use it. Cover each worked example and try it before reading the solution. There is no calculator in the real ESAT, so the numbers here are friendly. Finish with the self-check, then the practice set.

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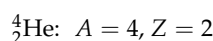
1 Atoms, nuclide notation and isotopes (P7.1)

Every atom has a tiny, dense, positively charged **nucleus** surrounded by electrons. The nucleus contains two kinds of particle, together called **nucleons**: **protons** (charge +1) and **neutrons** (no charge). The electrons carry charge -1 . Protons and neutrons have almost exactly the same mass, which we call 1 unit; an electron is about $\frac{1}{1840}$ of that, so almost all the mass of the atom is in the nucleus. A neutral atom has equal numbers of protons and electrons, so the charges cancel.



helium: 2 protons, 2 neutrons, 2 electrons

nuclide notation for this atom:



- proton: charge +1, mass 1
- neutron: charge 0, mass 1
- electron: charge -1 , mass $\approx \frac{1}{1840}$

Two numbers identify a nucleus.

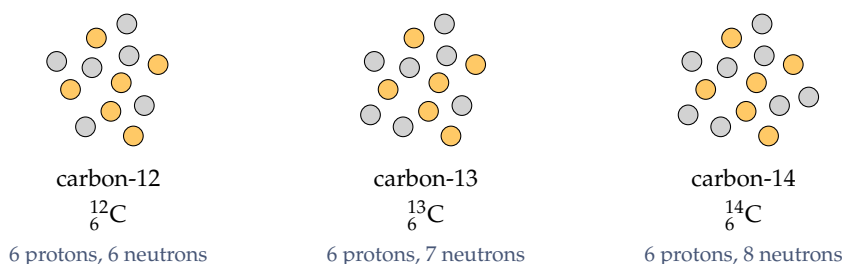
- The **atomic (proton) number** Z is the number of protons. It decides which element the atom is.
- The **mass (nucleon) number** A is the number of protons *plus* neutrons.

They are written together as **nuclide notation**, with the mass number on top and the atomic number underneath: ${}^A_Z\text{X}$. The number of neutrons is then

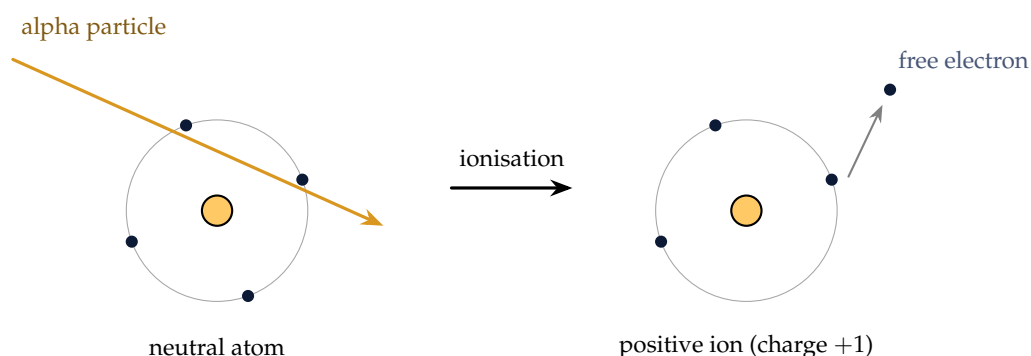
$$N = A - Z.$$

For ${}^{14}_6\text{C}$ the number of protons is 6 and the number of neutrons is $14 - 6 = 8$.

Isotopes are atoms of the same element (same Z) with different numbers of neutrons (different A). They have identical chemistry, because chemistry depends on the electrons, but they can differ in stability: some isotopes are stable, others are radioactive.



Ions and ionisation. An atom that loses or gains electrons is no longer neutral: it becomes an **ion**. Losing an electron leaves a positive ion. **Ionisation** is the process of knocking electrons off atoms, and radiation that can do so is called **ionising radiation**.



Worked example: reading nuclide notation

Copper-65 is written $^{65}_{29}\text{Cu}$. How many protons, neutrons and (in a neutral atom) electrons does it have? Copper-63 is another isotope of copper: how many neutrons does that have? Protons = $Z = 29$. Neutrons = $A - Z = 65 - 29 = 36$. A neutral atom has 29 electrons. Copper-63 has the same $Z = 29$, so $63 - 29 = 34$ neutrons.

Common mistakes

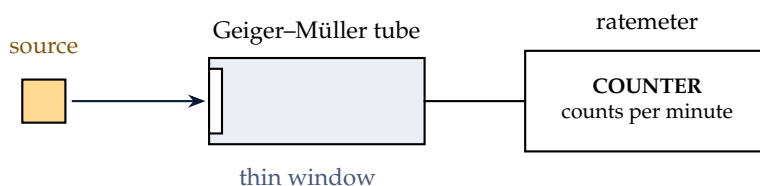
- Taking the mass number as the number of neutrons. Neutrons = $A - Z$.
- Thinking isotopes have different numbers of protons. Different Z means a different *element*.
- Forgetting that electrons have almost no mass, so they are ignored in A .

2 Unstable nuclei and radioactive decay (P7.2)

Protons repel each other, and what holds a nucleus together is a short-range attraction between nucleons. Some combinations of protons and neutrons are stable. Others, usually those with too many neutrons, too few, or simply too many nucleons altogether, are not: sooner or later they change. When an unstable nucleus changes it releases energy and (usually) a particle, in a process called **radioactive decay**. The radiation comes straight from the nucleus, and is not affected by temperature, pressure, or chemical reactions.

Decay is random. For a single nucleus there is no way to say *when* it will decay: it might be in the next second or in a million years. Nothing you do can speed it up or slow it down, and the nucleus does not “know” how long it has existed. What you *can* say is how likely a decay is. For a very large number of nuclei, a fixed fraction decays in each interval of time, and this regularity is described by the half-life (Section 6).

Measuring radiation. The usual detector is the **Geiger–Müller (GM) tube**. Ionising radiation entering the tube ionises the gas inside, producing a tiny pulse of current. A counter records the pulses as a **count rate**, in counts per second or counts/min.



The count rate is proportional to the number of decays per second, which is called the **activity** of the source and measured in becquerel (Bq): 1 Bq is one decay per second.

Background radiation. Even with no source nearby a GM tube clicks. This is **background radiation**, always present, from natural sources (radon gas seeping from rocks, which is the largest in many parts of the UK, cosmic rays from space, and rocks, soil, buildings, food and drink that contain traces of radioactive isotopes) and man-made ones (medical X-rays, and small amounts from nuclear power and past weapons tests). In every careful experiment you measure the background first, and subtract it from readings taken with the source.

Worked example: subtracting background

With no source present a GM tube counts 90 counts in 3 min. With a source in place it counts 690 in 3 min. What is the count rate due to the source?

Background rate = $90/3 = 30$ counts/min. Total rate = $690/3 = 230$ counts/min. Rate due to the source = $230 - 30 = 200$ counts/min.

Common mistakes

- Forgetting to subtract the background count before calculating anything else.
- Believing that heating, cooling or chemically combining the source changes how fast it decays. It does not.
- Saying a particular nucleus "is due" to decay. Decay is random; only large samples are predictable.

3 Alpha, beta and gamma decay and nuclear equations (P7.2)

Three kinds of radiation are emitted, which differ in what they are.

Alpha (α) decay. The nucleus emits an **alpha particle**, which is the same as a helium nucleus: 2 protons and 2 neutrons, written ${}^4_2\text{He}$ (or ${}^4_2\alpha$). Its charge is +2 and its mass is 4 units. Large nuclei, such as uranium, do this.

Beta (β^-) decay. A neutron inside the nucleus turns into a proton, and a fast electron is created and ejected. This electron, written ${}^0_{-1}\text{e}$, is the beta particle. It comes from the nucleus, not from the electron shells. (Another particle, an antineutrino, is emitted at the same time; you do not need it for the ESAT.) Nuclei with too many neutrons do this.

Gamma (γ) decay. After an alpha or beta decay the new nucleus is often left with surplus energy. It gets rid of it by emitting a **gamma ray**, a high-energy electromagnetic wave, with no mass and no charge. Gamma emission does not change the numbers of protons and neutrons.

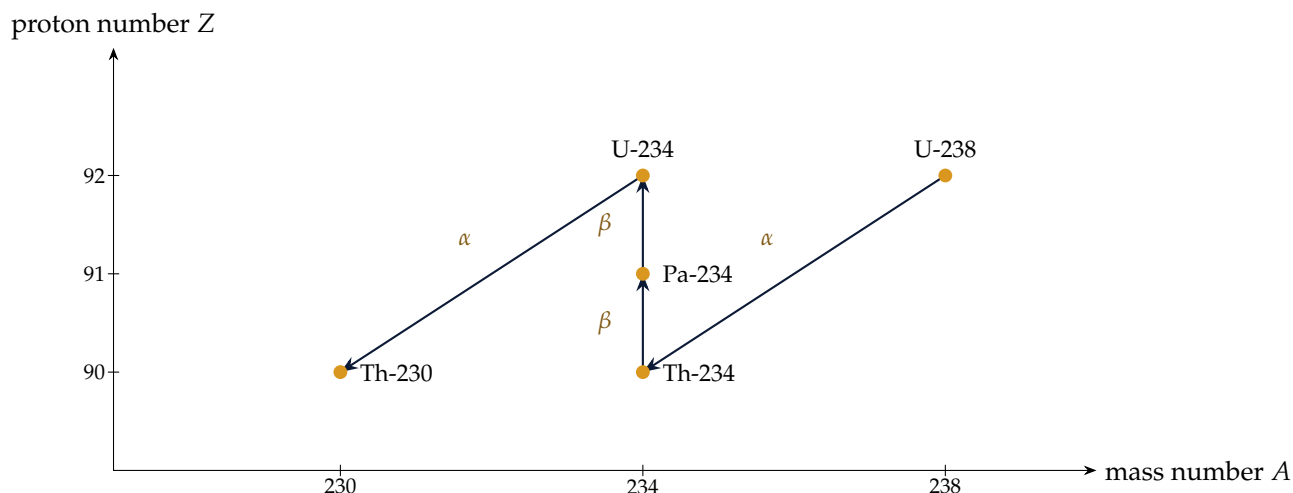
Nuclear equations. A decay is written like a chemical equation, but with whole nuclei, and it must balance in two ways: the *mass numbers* (top) must add up to the same total on both sides, and so must the *atomic numbers* (bottom), because nucleons and charge are conserved.



The rules that follow are all you need:

decay	mass number A	atomic number Z
alpha	decreases by 4	decreases by 2
beta	unchanged	increases by 1
gamma	unchanged	unchanged

Beta decay increases Z by one because a neutron has become a proton: the total number of nucleons is unchanged, so A stays the same. We can follow a chain of decays on a grid of Z against A : an alpha decay moves the nucleus down and to the left (by 2 in Z and 4 in A), and a beta decay moves it straight up by one.



Worked example: completing a nuclear equation

Radium-226 $^{226}_{88}\text{Ra}$ decays by emitting an alpha particle. Write the equation and identify the product, given that $Z = 86$ is radon (Rn).

Alpha decay: A falls by 4 to 222 and Z falls by 2 to 86. $^{226}_{88}\text{Ra} \rightarrow ^{222}_{86}\text{Rn} + ^4_2\text{He}$. Check: $226 = 222 + 4$ and $88 = 86 + 2$.

Worked example: two decays in a row

A nucleus $^{234}_{90}\text{Th}$ emits a beta particle and then another beta particle. What is the nucleus formed?

First beta: $A = 234, Z = 91$. Second beta: $A = 234, Z = 92$. The final nucleus is $^{234}_{92}\text{U}$ (uranium-234), which is an isotope of $^{238}_{92}\text{U}$.

Common mistakes

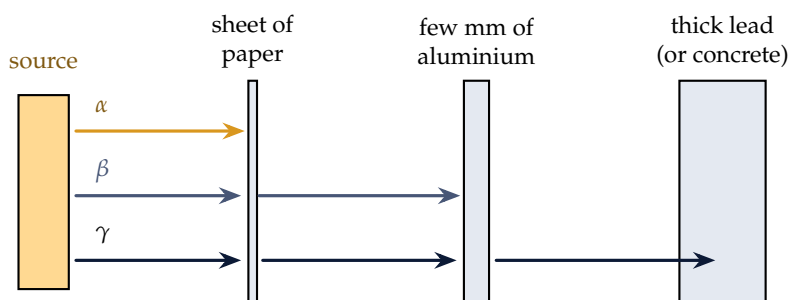
- Getting beta decay wrong by changing A . In beta decay A stays the same and Z goes up by 1.
- Forgetting that the beta particle is an electron from the nucleus, with charge -1 and bottom number -1 .
- Writing equations that balance in A but not in Z . Always check both rows.

4 Properties of the three radiations (P7.3)

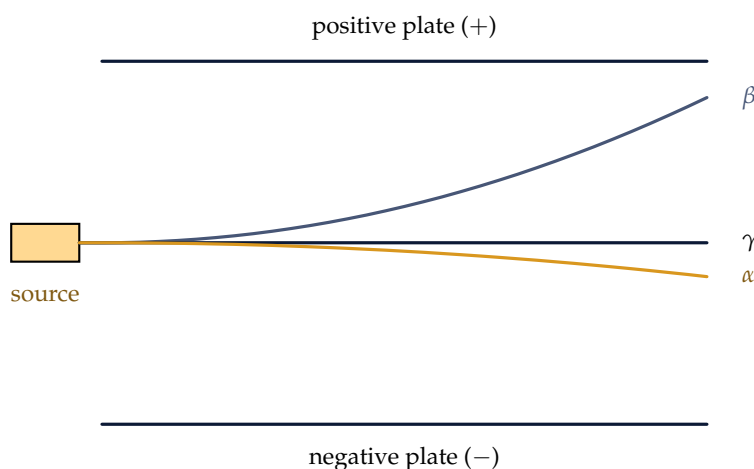
The radiations behave differently when they meet matter, and ESAT questions test this repeatedly. Three properties matter.

Ionising power. As radiation passes through matter it knocks electrons off the atoms, losing energy each time. An alpha particle is large and heavily charged ($+2$) and does this very easily, so it is **strongly ionising**. A beta particle is lighter and fast: **moderately ionising**. Gamma rays carry no charge and interact rarely: **weakly ionising**.

Penetration. A strongly ionising radiation loses its energy quickly and so does not get far. An alpha particle is stopped by a few centimetres of air, a sheet of paper or the outer layer of skin. A beta particle travels about a metre in air and is stopped by a few millimetres of aluminium. Gamma rays travel very far, are only reduced (never stopped completely) by absorbers, and need thick lead or several metres of concrete to cut them substantially.



Behaviour in electric and magnetic fields. Charged particles are deflected by electric and magnetic fields, and neutral rays are not. Between two charged plates a positively charged alpha particle bends towards the negative plate, while a negatively charged beta particle bends towards the positive plate, in the opposite direction and *much more*, because it has so little mass. Gamma rays travel straight on.



	alpha	beta (β^-)	gamma
what it is	helium nucleus (2p, 2n)	fast electron from the nucleus	electromagnetic wave
charge	+2	-1	0
ionising power	strong	moderate	weak
stopped by	paper, a few cm of air, skin	a few mm of aluminium	thick lead, metres of concrete
in a field	small deflection, towards -	large deflection, towards +	none

Notice the trade-off: the more strongly a radiation ionises, the less far it penetrates.

Worked example: which radiation?

A source is placed in front of a GM tube. The count rate is high. A sheet of paper placed between them makes no difference. A 5 mm sheet of aluminium reduces the count rate to the background level. Which radiation does the source emit?

Paper makes no difference, so there is no alpha. Aluminium removes the radiation, so it is not gamma (which would still pass through aluminium). The source emits beta radiation.

Common mistakes

- Mixing up the directions of deflection. Positive particles go towards the negative plate (alpha), negative particles towards the positive plate (beta).
- Saying that gamma rays are the most ionising because they are the most penetrating. They are the *least* ionising and the *most* penetrating.
- Thinking beta particles are electrons from the electron shells. They are made in the nucleus.

5 Uses and hazards of radioactivity (P7.3)

Hazards. Ionising radiation damages living cells: it can damage DNA, which may kill the cell or, if it survives, may cause mutations that lead to cancer. Radiation sickness follows very high doses. There are two distinct ways a person can be exposed.

- **Irradiation:** exposure to radiation from a source outside the body. Alpha is blocked by skin and air, so an external alpha source is not very dangerous; gamma, which penetrates, is.
- **Contamination:** getting radioactive atoms on or inside the body (by breathing or swallowing them). Now an alpha emitter is the most dangerous of all, because all of its energy is deposited in the surrounding tissue, and the source cannot be removed.

Precautions: handle sources with tongs, keep them in lead-lined containers, limit the time of exposure, stay as far away as possible, and wear badges that measure the dose received.

Uses. The right radiation (and the right half-life) depends on the job.

- **Smoke alarms:** a small *alpha* source ionises the air in the alarm, producing a steady current. Smoke particles absorb the alpha particles, the current drops, and the alarm sounds. Alpha is ideal: it ionises strongly but is stopped by the casing, and the source has a long half-life.
- **Thickness monitoring** of paper or metal foil: a *beta* source on one side and a detector on the other. If the sheet gets thicker, fewer particles get through, and the rollers are adjusted. (Alpha would be stopped completely; gamma would hardly notice.)
- **Medical tracers:** a *gamma* emitter with a short half-life of hours is swallowed or injected, and a detector outside the body follows it. Gamma passes out of the body; the short half-life means it soon disappears.
- **Radiotherapy and sterilisation:** beams of gamma rays kill cancer cells, or kill bacteria on surgical instruments and food, which then need no heating.
- **Radioactive dating:** the proportion of carbon-14 remaining in once-living material gives its age (see Section 6).

Exam tip

For any “which source?” question, check three things: the *type* (must get through, or be stopped, as the job requires), the *half-life* (long if it must last, short if it must not stay in the body), and *where* the source is (inside or outside the body).

Worked example: choosing a source

A hospital wants a tracer to be injected into a patient and detected from outside the body. Which of these is the best choice: (A) an alpha emitter, half-life 6 h; (B) a gamma emitter, half-life 6 h; (C) a gamma emitter, half-life 6000 years? Alpha cannot leave the body, ruling out A. A source of half-life 6000 years would stay radioactive in the patient for ever, ruling out C. The best choice is B.

Common mistakes

- Saying alpha sources are the most dangerous in every situation. Outside the body they are the least; inside, the most.
- Using a long half-life for a medical tracer. The source must decay away quickly.
- Confusing irradiation and contamination.

6 Half-life (P7.4)

Although a single decay is random, a large sample has a very regular pattern. The **half-life** of an isotope is the time taken for **half of the radioactive nuclei in a sample to decay**. Equivalently, it is the time for the activity (or the count rate) of the sample to fall to half.

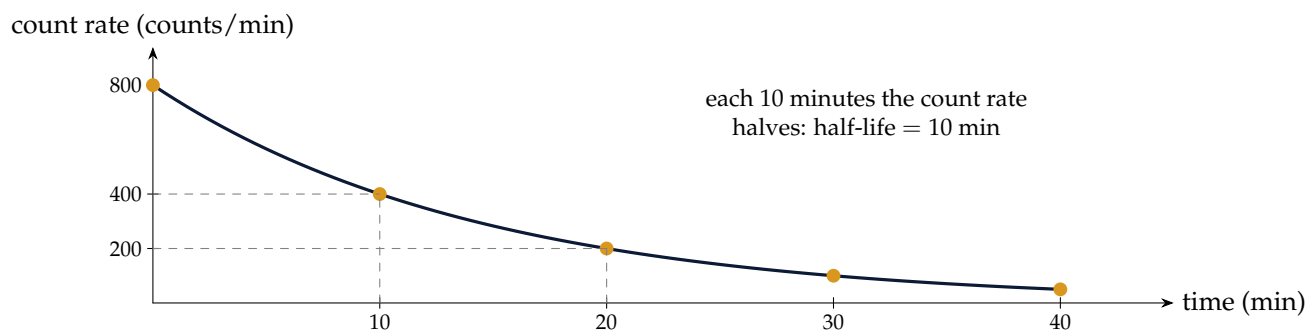
start		all 16 nuclei undecayed (fraction 1)
after 1 half-life		8 undecayed (fraction $\frac{1}{2}$)
after 2 half-lives		4 undecayed (fraction $\frac{1}{4}$)
after 3 half-lives		2 undecayed (fraction $\frac{1}{8}$)

Start with 16 undecayed nuclei (shaded). After one half-life, half of them (8) are left, after two half-lives half of those (4), after three, 2. Every half-life the amount halves, whatever the starting amount: the number left after n half-lives is

$$\text{fraction left} = \left(\frac{1}{2}\right)^n, \quad n = \frac{\text{time elapsed}}{\text{half-life}}.$$

The decay never quite reaches zero: halving, halving, halving, forever. Half-lives vary enormously: polonium-214 lasts a fraction of a second, technetium-99m (a medical tracer) 6 hours, carbon-14 about 5700 years and uranium-238 about 4.5 billion years.

The decay graph. Plotting count rate against time gives a falling curve that gets ever flatter. To find the half-life from the graph, read off the time for the count rate to fall from any value to half of it. The answer should be the same wherever you start.



In the graph the count rate falls from 800 to 400 in 10 minutes, and from 400 to 200 in the next 10 minutes, so the half-life is 10 minutes. (From 800 to 200 takes two half-lives, 20 minutes: also consistent.)

Carbon dating. Living things take in carbon, including a constant tiny fraction of radioactive carbon-14. When they die, no more is taken in, and the carbon-14 decays with a half-life of about 5700 years. Measuring how much carbon-14 is left in a piece of wood therefore tells us how many half-lives have passed since it died.

With background radiation. Always subtract the background first: it is the *net* count rate from the source that halves each half-life, not the total.

Worked example: fraction remaining

A sample has a half-life of 20 min. What fraction of the nuclei is undecayed after 1 h?
 $60/20 = 3$ half-lives. Fraction left = $\left(\frac{1}{2}\right)^3 = \frac{1}{8}$.

Worked example: working backwards

After 12 d, 5 g of a radioactive isotope remain. Its half-life is 4 d. How much was there at the start?
 $12/4 = 3$ half-lives. Going back, double three times: $5 \rightarrow 10 \rightarrow 20 \rightarrow 40$. The sample began as 40 g.

Worked example: count rate with background

A source gives a total count rate of 140 counts/min. The background is 20 counts/min. The half-life is 30 min. What total count rate will be recorded after 1 h?
 Net rate now = $140 - 20 = 120$. After $60/30 = 2$ half-lives it is $120/4 = 30$. Total recorded = $30 + 20 = 50$ counts/min.

Worked example: age from carbon-14

A fragment of wood has $\frac{1}{8}$ of the carbon-14 activity of fresh wood. How old is it? (Half-life of carbon-14 = 5700 years.)
 $\frac{1}{8} = (\frac{1}{2})^3$, so three half-lives have passed: $3 \times 5700 = 17100$ years.

Common mistakes

- Saying that half the half-life means one quarter of the sample, or that after two half-lives nothing is left. After two half-lives $\frac{1}{4}$ remains.
- Halving the *total* count rate rather than the net count rate. Subtract the background, halve, then add it back.
- Reading a half-life from a graph as the time to reach zero. It is the time to *halve*.

Check yourself

Try these without looking back, then compare with the answers on the next page.

1. How many neutrons are in a nucleus of ${}_{92}^{238}\text{U}$?
2. What are isotopes?
3. Which radiation is a helium nucleus? Which is an electromagnetic wave?
4. A nucleus ${}_{84}^{214}\text{Po}$ emits an alpha particle. What is the new nucleus?
5. What happens to A and Z in beta decay?
6. Which radiation is stopped by paper? Which needs thick lead?
7. A source has a half-life of 2 h and a count rate of 400 counts/min (background ignored). What is the rate after 6 h?
8. Why is an alpha source more dangerous than a gamma source when swallowed?

Answers to the self-check

1. $238 - 92 = 146$.
2. Atoms of the same element (same proton number) with different numbers of neutrons.
3. Alpha; gamma.
4. $A = 210, Z = 82$: $^{210}_{82}\text{Pb}$.
5. A is unchanged and Z increases by 1.
6. Alpha; gamma.
7. Three half-lives: $400/8 = 50$ counts/min.
8. All its energy is absorbed inside the body, where it ionises strongly, and it cannot be removed.

Next step

Heurisco's *ESAT Physics: Radioactivity Practice Set* has twenty original exam-style questions on this lesson, with diagrams and decay graphs, in order of difficulty, with a full worked solution and a note on the trap in each.