Physics Units 1 & 2

Chapter 3 — Radiation from the nucleus

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Theory

All ordinary matter is made of **atoms**. Each atom has a tiny, dense, positively charged core called the **nucleus**, with electrons surrounding it. The nucleus is about 10^{-15} m across, while the whole atom is about 10^{-10} m across — the atom is roughly $100\,000$ times wider than its nucleus. Almost all of the atom's mass sits in the nucleus.

Protons, neutrons and nucleons. The nucleus contains two kinds of particle. **Protons** carry a positive charge equal in size to the electron's charge. **Neutrons** carry no charge. Protons and neutrons are known collectively as **nucleons**. The number of protons in a nucleus is the **atomic number**, Z, and it decides which element the atom is: every carbon atom has $Z = 6$, every uranium atom has $Z = 92$. The total number of nucleons is the **mass number**, A, so the number of neutrons is

$$N = A - Z.$$

A nucleus is written in **nuclide notation**, ${}^{A}_{Z}X$, where X is the element's chemical symbol. A particular kind of nucleus, identified by its Z and A, is called a **nuclide**. For example, ${}^{12}_{6}\mathrm{C}$ is a carbon nuclide with 6 protons and $12 - 6 = 6$ neutrons, and ${}^{238}_{92}\mathrm{U}$ is a uranium nuclide with 92 protons and $238 - 92 = 146$ neutrons. Two nuclides with the same Z but different N are **isotopes** of the same element: ${}^{12}_{6}\mathrm{C}$ and ${}^{14}_{6}\mathrm{C}$ are both carbon, but carbon-14 has two more neutrons.

The problem of the nucleus. Protons repel each other through the **electrostatic force** — the force between charged particles, repulsive between like charges. Inside a nucleus the protons are extraordinarily close together, about $1\,\mathrm{fm}$ apart (a **femtometre**, fm, is 10^{-15} m). At that separation two protons repel each other with a force of about $2.3 \times 10^{2}\,\mathrm{N}$ — roughly the force due to gravity on a $23\,\mathrm{kg}$ mass — an enormous push on a particle so small. The gravitational attraction between the same two protons is only about $1.9 \times 10^{-34}\,\mathrm{N}$, smaller than the electrostatic repulsion by a factor of about 10^{36}. Gravity is far too weak to matter inside a nucleus, so the question of why the nucleus does not fly apart demands a third force.

The strong nuclear force. That force is the **strong nuclear force**. Its key properties are:

- It is **attractive** and acts between *all* pairs of nucleons — proton–proton, neutron–neutron and proton–neutron alike. At extremely small separations it becomes repulsive, which stops the nucleons collapsing into one another.
- It is very much stronger than the electrostatic force at nuclear distances — roughly 100 times the electrostatic repulsion between two protons $1\,\mathrm{fm}$ apart. It is the strongest of the forces acting inside the nucleus, which is how it gets its name.
- It is **short range**: it acts only over distances of about $1–3\,\mathrm{fm}$. Beyond about $3\,\mathrm{fm}$ it falls effectively to zero.

The strong nuclear force is the "glue" that holds the nucleus together.

The balance that decides stability. The two main forces in the nucleus behave very differently with distance. The electrostatic repulsion is **long range**: every proton repels every other proton in the nucleus, no matter where the other proton sits. The strong nuclear force is **short range**: each nucleon is attracted only by its immediate neighbours. A nucleus is **stable** when the net effect of the strong force holds its nucleons together. If the repulsions win, the nucleus is **unstable**: it will, on its own and without any outside trigger, change into a different nucleus and release energy and particles as it does so. This spontaneous change is called **radioactive decay**, and an unstable nucleus is **radioactive**. The radiation released in these decays is the subject of Section 3B.

The role of neutrons. Neutrons add strong-force attraction but no electrostatic repulsion, because they have no charge. Adding neutrons therefore adds "glue" without adding any extra pushing-apart. In light stable nuclei the numbers of protons and neutrons are about equal: ${}^{4}_{2}\mathrm{He}$ has 2 and 2, ${}^{12}_{6}\mathrm{C}$ has 6 and 6, ${}^{16}_{8}\mathrm{O}$ has 8 and 8. In heavier stable nuclei the neutrons outnumber the protons, and the gap grows with size: ${}^{56}_{26}\mathrm{Fe}$ has 26 protons and 30 neutrons, while the heaviest stable nuclide, ${}^{208}_{82}\mathrm{Pb}$, has 82 protons and 126 neutrons. The neutron-to-proton ratio, N / Z, rises from about 1.0 for light stable nuclei to about 1.5 for the heaviest stable ones.

A nucleus whose neutron-to-proton balance is wrong for its size — too many neutrons, or too few — is unstable and radioactive. There is also an upper size limit: every nucleus with more than 82 protons is unstable, whatever its neutron number, because the long-range repulsion between so many protons can no longer be matched by the short-range strong force. Uranium-238 ($^{238}_{92}U$) is unstable, for example, but it decays so slowly — its half-life is about 4.5 billion years, comparable to the age of Earth — that it is still found naturally in the ground. (The idea of a half-life is developed in Section 3C.)

The weak nuclear force. The forces above pull nucleons together or push them apart, but none of them changes what a nucleon *is*. The third force in the nucleus can. The **weak nuclear force** acts over an even shorter range than the strong force (about $10^{-18}\,\mathrm{m}$) and is far weaker than the strong force at nuclear distances, but it has a unique ability: it can transform a neutron into a proton, or a proton into a neutron. When a nucleus has the wrong neutron-to-proton balance, it is the weak force that allows the nucleus to adjust its composition and move toward a stable arrangement. The decays this produces — beta decays, in which the changing nucleon ejects a fast electron or a particle called a positron — are covered in Section 3B.

The three forces are summarised below.

Force	Acts between	Effect in the nucleus	Relative strength at about $1\,\mathrm{fm}$	Range
Electrostatic	Charged particles (proton–proton)	Repels protons; pushes the nucleus apart	1 (reference)	Long range — acts across the whole nucleus
Strong nuclear	All nucleon pairs (p–p, n–n, p–n)	Attracts; holds the nucleus together	About 100	Short range — about $1–3\,\mathrm{fm}$
Weak nuclear	Nucleons, during transformations	Changes a neutron into a proton, or a proton into a neutron, enabling decay	Much less than 1	Very short range — about $10^{-18}\,\mathrm{m}$

Nuclear stability is therefore a contest between two forces: the long-range electrostatic repulsion of the protons, which tries to break the nucleus apart, and the short-range strong nuclear attraction of all the nucleons, which holds it together. Neutrons strengthen the attractive side without strengthening the repulsive side, and the weak force provides the route by which an unbalanced nucleus changes itself. The energy released when nuclei rearrange, and why some nuclear releases are far larger than others, is examined in Chapter 4.

Units 3 & 4 preview. This section treats the electrostatic force qualitatively — attraction and repulsion, and how the force changes with distance. At Units 3 & 4 the electric force is modelled quantitatively using electric fields. Nothing in this preview is assessed in this chapter's topic test.

Worked examples

Example 1 — scaffolded

Complete the table of proton, neutron and nucleon numbers for the nuclides carbon-12, $^{12}_{6}C$, carbon-14, $^{14}_{6}C$, and uranium-238, $^{238}_{92}U$. State which of the three are isotopes of one another.

Working	Comment
Z is the lower number in the symbol: $Z=6$ for both carbon nuclides, $Z=92$ for uranium.	The atomic number Z is the number of protons.
A is the upper number: $A=12, 14, 238$.	The mass number A is the total number of nucleons (protons + neutrons).
$N=A-Z$: carbon-12 gives $12-6=6$; carbon-14 gives $14-6=8$; uranium-238 gives $238-92=146$.	The neutron number is the difference between A and Z.
Carbon-12 and carbon-14 both have $Z=6$ but different	Same element, different neutron number: they are

Working	Comment
N (6 and 8).	isotopes. Uranium has a different Z, so it is not an isotope of carbon.

Example 2 — scaffolded

Two protons $1.0\,\mathrm{fm}$ apart repel each other with an electrostatic force of about $2.3 \times 10^{2}\,\mathrm{N}$. The gravitational attraction between them is about $1.9 \times 10^{-34}\,\mathrm{N}$. (a) Calculate how many times larger the electrostatic repulsion is than the gravitational attraction. (b) State what your answer implies about the force that holds the nucleus together.

Working	Comment
$\dfrac{2.3 \times 10^{2}}{1.9 \times 10^{-34}}$	Divide the larger force by the smaller.
$= \dfrac{2.3}{1.9} \times 10^{2-(-34)} = 1.2 \times 10^{36}$ (2 s.f.)	Divide the numbers and subtract the indices; both given values have two significant figures.
The electrostatic repulsion is about 10^{36} times the gravitational attraction.	Gravity is far too weak to overcome the repulsion.
A third force, stronger than the electrostatic repulsion and attractive, must act between the protons.	This is the strong nuclear force.

Example 3 — unscaffolded

A student says: *"Neutrons have no electric charge, so they cannot have any effect on the forces inside a nucleus."* Use the forces in the nucleus to evaluate this claim.

The claim is wrong. The forces inside a nucleus are not only electrostatic. The **strong nuclear force** acts between *all* pairs of nucleons — including pairs that contain a neutron — so a neutron attracts its neighbouring nucleons just as a proton does. Because a neutron has no charge, it adds this strong-force attraction *without* adding any electrostatic repulsion. Adding neutrons therefore changes the balance of forces in the nucleus: it increases the total attraction holding the nucleus together while leaving the proton–proton repulsion unchanged. This is exactly why heavier stable nuclei need more neutrons than protons. The student's error is assuming that the only force that matters in the nucleus is the electrostatic force.

Example 4 — unscaffolded

The table lists three stable nuclides.

Nuclide	Protons Z	Neutrons N
oxygen-16, ${}^{16}_{8}\mathrm{O}$	8	8
iron-56, ${}^{56}_{26}\mathrm{Fe}$	26	30
lead-208, ${}^{208}_{82}\mathrm{Pb}$	82	126

Calculate the neutron-to-proton ratio N / Z for each nuclide to two significant figures, describe the trend, and explain the trend in terms of the forces in the nucleus.

The three ratios are: oxygen-16, $8/8 = 1.0$; iron-56, $30/26 = 1.2$; lead-208, $126/82 = 1.5$ (all to two significant figures). The trend is that the stable neutron-to-proton ratio increases as the nucleus gets heavier. The reason lies in the different ranges of the two main forces. The strong nuclear force is short range, so each nucleon is attracted only by its immediate neighbours; adding more nucleons increases the attraction only in proportion to the number of neighbours. The electrostatic repulsion is long range, so every proton repels every other proton in the nucleus, and the total repulsion grows rapidly as protons are added. Larger stable nuclei therefore need extra neutrons — which add strong-force attraction but no electrostatic repulsion — to keep the balance in favour of holding together.

Practice questions

Question 1 Complete the table below.

Nuclide	Protons	Neutrons	Nucleons
$^{4}_{2}He$			
$^{12}_{6}C$			
$^{14}_{6}C$			
$^{235}_{92}U$			
$^{208}_{82}Pb$			

Question 2 Write each of the following nuclei in nuclide notation $^{A}_{Z}X$. (a) 6 protons and 6 neutrons. (b) 6 protons and 8 neutrons. (c) 7 protons and 7 neutrons. (d) 8 protons and 8 neutrons. (e) Which of your four nuclei are isotopes of one another? Give a reason.

Question 3 The diameter of an atom is about 10^{-10} m and the diameter of its nucleus is about 10^{-15} m. (a) How many times wider is the atom than its nucleus? (b) If an atom were enlarged until it was 100 m across — roughly the length of the MCG — calculate the diameter the nucleus would have at the same scale.

Question 4 Every proton in a nucleus repels every other proton, so the number of repelling pairs grows quickly as protons are added. Two protons form 1 repelling pair; three protons form 3 pairs. (a) Show that a carbon-12 nucleus (6 protons) contains 15 repelling proton pairs. (b) Calculate the number of repelling proton pairs in a uranium-238 nucleus (92 protons). (c) Explain how your answers help to account for the extra neutrons found in heavy stable nuclei.

Question 5 The nuclei of three stable atoms are: nitrogen-14 (7 protons, 7 neutrons), oxygen-16 (8 protons, 8 neutrons) and fluorine-19 (9 protons, 10 neutrons). (a) Write each nuclide in the notation $^{A}_{Z}X$. (b) Calculate the neutron-to-proton ratio N / Z for each to two significant figures. (c) State whether these ratios are consistent with the pattern for light stable nuclei, and briefly justify your answer.

Question 6 Four nuclei are: calcium-40 (20 protons, 20 neutrons), carbon-14 (6 protons, 8 neutrons), lead-208 (82 protons, 126 neutrons) and uranium-238 (92 protons, 146 neutrons). (a) Calculate the neutron-to-proton ratio N / Z for each to two significant figures. (b) Two of these nuclei are stable and two are radioactive. Identify which is which. (c) Justify your identification in (b) using the stability ideas from this section.

Question 7 A helium-4 nucleus contains two protons about 1 fm apart, repelling each other with a force of about 2.3×10^{2} N, yet the nucleus holds together. Explain why the existence of the helium-4 nucleus is evidence for a force other than the electrostatic force and gravity.

Question 8 The strong nuclear force has a range of only about 1–3 fm. Explain why this means a nucleon is bound only to its immediate neighbours, and why this property sets a practical limit on how large a stable nucleus can be.

Question 9 Explain why adding one more proton to a nucleus tends to make it less stable, while adding one more neutron often makes it more stable.

Question 10 Deuterium, $^{2}_{1}H$, and tritium, $^{3}_{1}H$, are both isotopes of hydrogen. (a) State the number of protons and neutrons in each nucleus. (b) Calculate the neutron-to-proton ratio of each. (c) Deuterium is stable but tritium is radioactive. Identify the feature of tritium's nucleus that the stability model of this section flags as the problem.

Question 11 The strong and electrostatic forces can push nucleons around but cannot change one kind of nucleon into the other. State which force can make that change, and explain why this ability matters to a nucleus whose neutron-to-proton ratio is wrong.

Question 12 Define each term and give one example of it: (a) nucleon; (b) nuclide; (c) isotope; (d) radioactive.

Question 13 A nucleus contains 84 protons and 126 neutrons. (a) Write the nuclide in the notation $^{A}_{Z}X$. (Element 84 is polonium, Po.) (b) Predict whether this nucleus is stable or radioactive, giving the reason from this section.

Question 14 In a few sentences, explain why a nucleus full of mutually repelling protons does not fly apart. Your answer must name both forces involved and say what is different about their ranges.

Question 15 A media report claims that scientists have created a *stable* nucleus containing 114 protons and 184 neutrons. Use the stability model of this section to evaluate this claim.

Question 16 A uranium-238 nucleus is about 1.5×10^{-14} m across, but the strong nuclear force only reaches about 1–3×10^{-15} m. Explain why a proton on one side of the nucleus feels no strong-force attraction from a proton on the opposite side, yet still feels that proton's electrostatic repulsion.

Question 17 A nucleus made of two protons and no neutrons does not exist as a stable nucleus, yet helium-4 (two protons and two neutrons) is very stable. Explain the difference using the forces in the nucleus.

Question 18 Gold-197 ($^{197}_{79}Au$) is the only stable isotope of gold. (a) Calculate the number of neutrons in a gold-197 nucleus and its neutron-to-proton ratio to two significant figures. (b) Calcium-40 has a neutron-to-proton ratio of 1.0. Explain why gold needs the higher ratio.

Question 19 The diameter of a uranium-238 nucleus is about 1.5×10^{-14} m, and the diameter of a uranium atom is about 3.5×10^{-10} m. (a) Calculate how many times wider the atom is than its nucleus, to two significant figures. (b) If the nucleus were the size of a 1.0 cm marble, calculate the diameter of the atom on the same scale. Give your answer in metres.

Question 20 Using all three forces discussed in this section, write a short paragraph (4–6 sentences) explaining why some nuclei are stable while others are radioactive.

Answers

Question 1 He: 2, 2, 4; C-12: 6, 6, 12; C-14: 6, 8, 14; U-235: 92, 143, 235; Pb-208: 82, 126, 208. **Question 2** (a) $^{12}_{6}C$; (b) $^{14}_{6}C$; (c) $^{14}_{7}N$; (d) $^{16}_{8}O$; (e) (a) and (b): same $Z=6$, different neutron numbers. **Question 3** (a) $100\,000$ times; (b) $10^{-3}\,\mathrm{m}=1\,\mathrm{mm}$. **Question 4** (a) 15 pairs; (b) 4186 pairs; (c) see solution. **Question 5** (a) $^{14}_{7}N$, $^{16}_{8}O$, $^{19}_{9}F$; (b) 1.0, 1.0, 1.1; (c) yes — all near 1, as for light stable nuclei. **Question 6** (a) 1.0, 1.3, 1.5, 1.6; (b) stable: calcium-40 and lead-208; radioactive: carbon-14 and uranium-238; (c) see solution. **Question 7** See solution — an attractive force stronger than the repulsion must act at $1\,\mathrm{fm}$: the strong nuclear force. **Question 8** See solution — short range limits binding to neighbours; long-range repulsion keeps growing with size. **Question 9** See solution — a proton adds repulsion as well as attraction; a neutron adds attraction only. **Question 10** (a) deuterium 1 p, 1 n; tritium 1 p, 2 n; (b) 1.0 and 2.0; (c) $N/Z=2.0$ is far too high for such a light nucleus. **Question 11** The weak nuclear force; it lets a neutron change into a proton (or the reverse), correcting an unbalanced N/Z. **Question 12** See solution for definitions and examples. **Question 13** (a) $^{210}_{84}Po$; (b) radioactive, because $Z=84>82$. **Question 14** See solution — the short-range strong nuclear attraction overcomes the long-range electrostatic repulsion. **Question 15** See solution — the model predicts the nucleus is unstable: $Z=114>82$. **Question 16** See solution — the separation exceeds the strong force's 1–$3\,\mathrm{fm}$ range but not the electrostatic force's long range. **Question 17** See solution — with no neutron there is no extra strong-force attraction to beat the repulsion; helium-4's two neutrons supply it. **Question 18** (a) 118 neutrons, $N/Z=1.5$; (b) see solution. **Question 19** (a) 2.3×10^{4} times; (b) $230\,\mathrm{m}$. **Question 20** See solution for a model paragraph.

Fully-worked solutions

Question 1 In $^{A}_{Z}X$ the lower number is Z (protons), the upper number is A (nucleons), and the neutron number is $N=A-Z$.

Nuclide	Protons Z	Neutrons $A-Z$	Nucleons A
$^{4}_{2}He$	2	$4-2=2$	4
$^{12}_{6}C$	6	$12-6=6$	12
$^{14}_{6}C$	6	$14-6=8$	14
$^{235}_{92}U$	92	$235-92=143$	235
$^{208}_{82}Pb$	82	$208-82=126$	208

Question 2 Add protons and neutrons to get A; the element is fixed by Z. (a) $A=6+6=12$: $^{12}_{6}C$, carbon-12. (b) $A=6+8=14$: $^{14}_{6}C$, carbon-14. (c) $A=7+7=14$: $^{14}_{7}N$, nitrogen-14. (d) $A=8+8=16$: $^{16}_{8}O$, oxygen-16. (e) Nuclei (a) and (b) are isotopes: both have $Z=6$ (both are carbon) but different neutron numbers, 6 and 8. Isotopes are defined by equal Z and different N. Note that (b) and (c) have the same A but different Z, so they are *not* isotopes — the same mass number alone does not make isotopes.

Question 3 (a) $\dfrac{10^{-10}}{10^{-15}}=10^{-10-(-15)}=10^{5}=100\,000$. The atom is about $100\,000$ times wider than its nucleus. (b) At the same scale the nucleus is $100\,000$ times smaller: $\dfrac{100}{100\,000}=10^{-3}\,\mathrm{m}=1\,\mathrm{mm}$. An atom the length of the MCG would have a nucleus about the size of a grain of sand.

Question 4 (a) With 6 protons, each proton repels the 5 others. Counting each pair once gives $\dfrac{6\times5}{2}=15$ pairs. (The division by 2 avoids counting the pair "proton 1 with proton 2" twice.) (b) For 92 protons: $\dfrac{92\times91}{2}=4186$ pairs. (c) Every proton added repels *all* the protons already present, so the total electrostatic repulsion grows very rapidly with Z — from 15 pairs in carbon to 4186 in uranium. The strong nuclear force does not grow the same way, because each nucleon attracts only its immediate neighbours. Heavy stable nuclei therefore need extra neutrons, which add strong-force attraction without adding any further repulsion, to keep the nucleus together.

Question 5 (a) ${}^{14}_{7}N$, ${}^{16}_{8}O$, ${}^{19}_{9}F$. (b) Nitrogen-14: $7/7 = 1.0$; oxygen-16: $8/8 = 1.0$; fluorine-19: $10/9 = 1.1$ (all to two significant figures). (c) Yes. Light stable nuclei have neutron-to-proton ratios close to 1, and all three values are at or very near 1. Fluorine-19's single extra neutron shows that small deviations from exactly 1 are still consistent with stability in light nuclei.

Question 6 (a) Calcium-40: $20/20 = 1.0$; carbon-14: $8/6 = 1.3$; lead-208: $126/82 = 1.5$; uranium-238: $146/92 = 1.6$ (all to two significant figures). (b) Stable: calcium-40 and lead-208. Radioactive: carbon-14 and uranium-238. (c) Calcium-40 is a light nucleus with $N/Z = 1.0$, exactly the pattern for light stable nuclei. Lead-208 has $Z = 82$ — the largest proton number that can be stable — and its ratio of 1.5 matches what a heavy stable nucleus needs. Carbon-14 is a light nucleus whose ratio of 1.3 is well above the value of about 1 that light nuclei need: it has too many neutrons, so it is unstable. Uranium-238 has $Z = 92$, which exceeds 82; no number of neutrons can make a nucleus that large stable, so it is radioactive (although it decays very slowly).

Question 7 Two protons $1\,\text{fm}$ apart repel each other strongly, and gravity between them is about 10^{36} times too weak to overcome that repulsion. Since the helium-4 nucleus holds together, there must be a further force acting between the nucleons that is attractive and stronger than the electrostatic repulsion at this separation. That force is the strong nuclear force. A stable nucleus is therefore direct evidence that the forces on the nucleons are not just electrostatic and gravitational.

Question 8 Because the strong nuclear force reaches only about $1\text{–}3\,\text{fm}$, a nucleon is attracted only by the nucleons immediately next to it; nucleons farther away across the nucleus contribute essentially no strong-force attraction. Meanwhile the electrostatic repulsion is long range, so every added proton repels every other proton in the nucleus, wherever it is. As the nucleus grows, the total repulsion keeps increasing while the binding from the strong force grows much more slowly. Beyond about 82 protons the repulsion cannot be matched, which is why there is a practical upper limit to the size of a stable nucleus.

Question 9 An added proton contributes both strong-force attraction (to its neighbours) and electrostatic repulsion (to *every* other proton in the nucleus, because the repulsion is long range). In any but the smallest nuclei the extra repulsion outweighs the extra attraction, so the nucleus becomes less stable. An added neutron contributes strong-force attraction but no electrostatic repulsion at all, because it has no charge — it adds glue without adding any extra pushing-apart. Adding a neutron therefore usually strengthens the balance in favour of stability, at least until the neutron-to-proton ratio grows too large.

Question 10 (a) Deuterium ${}^{2}_{1}H$: 1 proton, $2 - 1 = 1$ neutron. Tritium ${}^{3}_{1}H$: 1 proton, $3 - 1 = 2$ neutrons. (b) Deuterium: $N/Z = 1/1 = 1.0$. Tritium: $N/Z = 2/1 = 2.0$. (c) For such a light nucleus, stability requires a ratio near 1. Tritium's ratio of 2.0 means it has too many neutrons for its single proton, so the model flags it as unstable — tritium is radioactive. (The decay it undergoes to correct this imbalance is a beta decay, covered in Section 3B.)

Question 11 The force is the **weak nuclear force**. It can change a neutron into a proton, or a proton into a neutron. This matters because a nucleus with the wrong neutron-to-proton ratio cannot fix that ratio by being pushed or pulled: the number of each kind of nucleon must actually change. The weak force provides the only mechanism for that change, and it is therefore the force behind the decays by which unbalanced nuclei move toward stability.

Question 12 (a) **Nucleon**: a particle found in the nucleus — either a proton or a neutron. Example: the neutron in ${}^{2}_{1}H$. (b) **Nuclide**: a particular kind of nucleus, identified by its proton number Z and mass number A. Example: ${}^{12}_{6}C$. (c) **Isotope**: one of two or more nuclides with the same proton number Z but different neutron numbers. Example: ${}^{12}_{6}C$ and ${}^{14}_{6}C$ are isotopes of carbon. (d) **Radioactive**: describing a nucleus that is unstable and decays spontaneously, changing into a different nucleus and releasing radiation. Example: ${}^{238}_{92}U$.

Question 13 (a) $A = 84 + 126 = 210$, so the nuclide is ${}^{210}_{84}Po$ (polonium-210). (b) It is predicted to be radioactive. Every nucleus with more than 82 protons is unstable, whatever its neutron number, and this nucleus has $Z = 84$. Its 126 neutrons cannot compensate for the long-range repulsion of 84 protons.

Question 14 Model answer: The protons in a nucleus repel one another through the **electrostatic force**, which is long range, so every proton repels every other proton. The nucleus holds together because the nucleons also attract one another through the **strong nuclear force**, which is about 100 times stronger than the electrostatic repulsion at nuclear separations. The crucial difference is range: the strong force acts only over about $1\text{–}3\,\text{fm}$, binding each nucleon to its neighbours, while the electrostatic force reaches across the whole nucleus. In a stable nucleus — helped by neutrons, which add attraction without adding repulsion — the strong nuclear attraction wins.

Question 15 Model answer: The claim is not supported by the stability model. A nucleus with 114 protons has $Z=114$, well above the limit of 82 protons beyond which no stable nucleus exists. The N / Z ratio of $184/114=1.6$ is similar to that of the heaviest stable nuclei, but adding neutrons cannot solve the problem at this size, because every one of the 114 protons repels every other through the long-range electrostatic force while the strong force binds only neighbours. The model therefore predicts the nucleus is unstable and radioactive; a report calling it stable would need to show evidence that contradicts this, and the word "stable" is very likely being used loosely to mean "has been made to exist briefly".

Question 16 The separation between a proton on one side of the uranium nucleus and a proton on the opposite side is about $1.5\times10^{-14}\,\text{m}$. That is at least five times larger than the $1\text{–}3\times10^{-15}\,\text{m}$ range of the strong nuclear force, so the strong-force attraction between those two protons is effectively zero. The electrostatic force, however, is long range: it does not cut off at a few femtometres, so the two protons still repel each other across the full width of the nucleus. This is precisely why the repulsion problem gets worse in large nuclei while the strong-force "glue" does not keep pace.

Question 17 Two protons alone repel each other through the electrostatic force, and the only attraction available is the strong force between that one pair — with no neutrons there is no additional strong-force attraction to tip the balance, so no stable two-proton nucleus exists. Helium-4 has two protons *and* two neutrons. The neutrons attract all their neighbours through the strong force but repel no one, because they have no charge, so they add enough extra attraction to overcome the proton–proton repulsion. The result is a very stable nucleus.

Question 18 (a) Neutrons: $N=A-Z=197-79=118$. Ratio: $N/Z=118/79=1.5$ (2 s.f.). (b) Gold is a heavy nucleus. As Z grows, every proton repels every other proton through the long-range electrostatic force, so the total repulsion grows rapidly, while the short-range strong force only binds neighbouring nucleons. Heavy stable nuclei therefore need extra neutrons — which add strong-force attraction without adding any repulsion — to keep the nucleus together. Calcium-40 is light enough that a ratio of 1.0 is sufficient, but gold needs the higher ratio of about 1.5.

Question 19 (a) $\dfrac{3.5\times10^{-10}}{1.5\times10^{-14}}=\dfrac{3.5}{1.5}\times10^{-10-(-14)}=2.3\times10^{4}$ (2 s.f.). The atom is about $23\,000$ times wider than its nucleus. (b) On the same scale the atom's diameter is $1.0\,\text{cm}\times2.3333\times10^{4}=2.3\times10^{4}\,\text{cm}=230\,\text{m}$ (2 s.f.). A uranium nucleus the size of a marble would sit at the centre of an atom more than two hundred metres across.

Question 20 Model paragraph: A nucleus is a contest between three forces. The protons repel one another through the long-range **electrostatic force**, so every proton pushes on every other proton and the total repulsion grows quickly as the nucleus gets larger. The nucleons are held together by the **strong nuclear force**, which is far stronger at nuclear separations but acts only over $1\text{–}3\,\text{fm}$, so each nucleon is bound only to its neighbours. Neutrons help because they add strong-force attraction without adding any electrostatic repulsion. A nucleus is **stable** when this balance holds — roughly equal numbers of protons and neutrons for light nuclei, and more neutrons than protons for heavy ones. When the balance is wrong, either because the neutron-to-proton ratio is off or because there are more than 82 protons, the nucleus is unstable, and the **weak nuclear force** allows it to change a neutron into a proton or the reverse, decaying toward a more stable arrangement and releasing radiation as it does so.

Chapter 3 Radiation from the nucleus — 3B Alpha, beta and gamma radiation, and decay equations

Theory

In 3A we saw that the nucleus is held together by a competition between the repulsive electrostatic force between the positively charged protons and the attractive strong nuclear force between neighbouring nucleons. Some arrangements of protons and neutrons are unstable. An unstable nucleus changes by itself into a more stable arrangement, and the change releases energy. This spontaneous change is called **radioactive decay**, and the radiation released by the nucleus during the change is **nuclear radiation**.

An unstable isotope is called a **radioisotope** (or **radionuclide**). The decay of a radioisotope is **spontaneous**: it needs no outside trigger, and heating the sample, compressing it, or binding it into a chemical compound cannot switch the decay on or off, or change how quickly it happens. Any single nucleus decays at an unpredictable moment; the statistical pattern followed by a large number of decays is the subject of 3C.

Radiation from the nucleus comes in three main types, named **alpha (α)**, **beta (β)** and **gamma (γ)** as they were discovered in the early 1900s, in order of increasing penetrating power. Beta radiation itself has two forms, β^- and β^+. All four are **ionising radiation**: radiation with enough energy to knock electrons off atoms and molecules, converting them into charged particles called ions. How this ionising ability affects living tissue is examined in 3E; here we concentrate on what each radiation *is* and on how to write the equations that describe the decays that produce it.

Reading a nuclear equation. A nucleus is written in **nuclide notation**:

$${}^{A}_{Z}X$$

where X is the element's chemical symbol, A is the **mass number** (the total number of protons and neutrons) and Z is the **atomic number** (the number of protons). The atomic number decides which element the nucleus is: every nucleus with $Z = 6$ is carbon, every nucleus with $Z = 86$ is radon. Isotopes of the one element have the same Z but different A.

Every nuclear equation obeys two conservation rules.

1. **Mass number is conserved.** The sum of the top numbers on the left side equals the sum of the top numbers on the right side.
2. **Charge is conserved.** The sum of the bottom numbers on the left side equals the sum of the bottom numbers on the right side.

Decay also releases energy, which is carried away as kinetic energy of the emitted particles and as gamma radiation. Where this energy comes from — the conversion of a small amount of mass — is taken up in Chapter 4; for now the energy released simply reminds us that the products leave the nucleus more stable than before.

These two rules let you complete any decay equation. A reliable method:

1. Write the parent nucleus on the left and the emitted particle on the right.
2. Use mass-number conservation to find the top number of the daughter nucleus.
3. Use charge conservation to find the bottom number of the daughter nucleus.
4. Use the atomic number to identify the daughter element (a periodic table supplies the name from Z).
5. Check that both the top and bottom numbers balance across the arrow.

Alpha radiation. An **alpha particle** (α) is a helium-4 nucleus: two protons and two neutrons bound together, written ${}^{4}_{2}\mathrm{He}$. It has charge $+2e$ ($+3.2 \times 10^{-19}$ C), mass number 4, and a mass about four times that of a proton — roughly 7000 times the mass of an electron. Alpha particles are typically emitted at about 5% of the speed of light. Alpha decay occurs in very heavy nuclei, such as uranium and radium: the nucleus sheds two protons and two neutrons in one package, becoming a different element two places lower in the periodic table.

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\mathrm{He}$$

For example, uranium-238 decays by alpha emission to thorium-234:

$^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$

Because of their large mass and double charge, alpha particles collide strongly with the atoms they pass: they are the **most strongly ionising** of the three radiations, and they lose their energy over a very short distance. An alpha particle travels only a few centimetres in air and is stopped by a sheet of paper or by the outer, dead layer of human skin.

Beta-minus radiation. A **beta-minus particle** (β^-) is an electron emitted from the nucleus, written $^{0}_{-1}e$. The electron is not one of the atom's orbiting electrons: it is created at the instant of decay when a neutron in the nucleus changes into a proton. The number of nucleons is unchanged, but the nucleus gains one proton, so the daughter is a different element, one place *higher* in the periodic table.

$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$

For example, carbon-14, which is used in radiocarbon dating of ancient material, decays to nitrogen-14:

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

Beta-minus particles are much lighter than alpha particles and carry a single charge, so they are **moderately ionising** and **moderately penetrating**: they travel up to about a metre in air and are absorbed by a few millimetres of aluminium.

Beta-plus radiation. A **beta-plus particle** (β^+) is a **positron**: the antimatter partner of the electron, with the same tiny mass but charge $+1e$ ($+1.6 \times 10^{-19}$ C). It is written $^{0}_{+1}e$. In beta-plus decay a proton in the nucleus changes into a neutron, so the daughter is one place *lower* in the periodic table.

$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e$

For example, carbon-11 decays to boron-11:

$^{11}_{6}C \rightarrow {}^{11}_{5}B + {}^{0}_{+1}e$

Positrons do not last long in ordinary matter. Within a very short distance a positron meets an electron, and the two **annihilate**: both particles disappear and their energy is carried away by two gamma rays travelling in opposite directions. Positron-emitting isotopes such as fluorine-18 are used in hospital PET scans; the medical imaging that exploits this annihilation is treated in Option 2.6. The ionising and penetrating properties of β^+ radiation are the same as those of β^-.

Gamma radiation. Gamma radiation (γ) is electromagnetic radiation of very high frequency — the same kind of wave as the light and radio waves of Chapter 1, but with a far shorter wavelength and far more energy per wave. It has no mass and no charge, and it travels at the speed of light, c.

Gamma rays are usually emitted immediately after an alpha or beta decay has left the daughter nucleus with excess energy — in an **excited state**, meaning a state with more energy than the nucleus's most stable arrangement. The nucleus drops to a lower-energy state by emitting a gamma ray. Since no nucleon leaves the nucleus, neither A nor Z changes, and the element is unchanged:

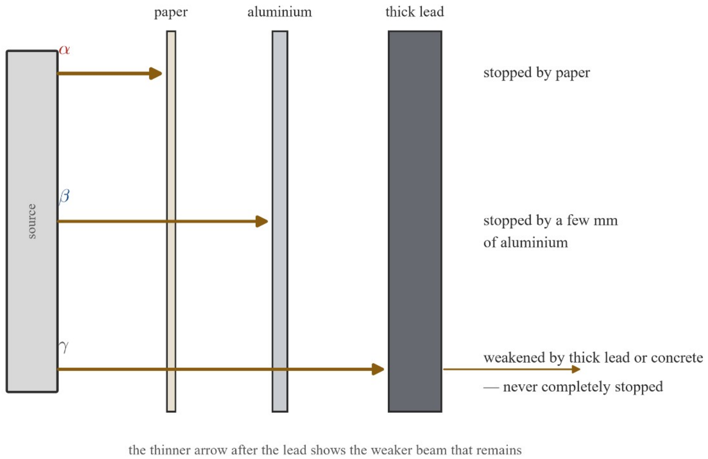
$^{A}_{Z}X^* \rightarrow {}^{A}_{Z}X + \gamma$

where the asterisk marks the excited nucleus. Gamma radiation is the **least ionising** but the **most penetrating** of the three: it travels large distances in air, and reducing it substantially requires many centimetres of lead or metres of concrete. No material stops it completely; enough thickness only reduces it to an acceptable level.

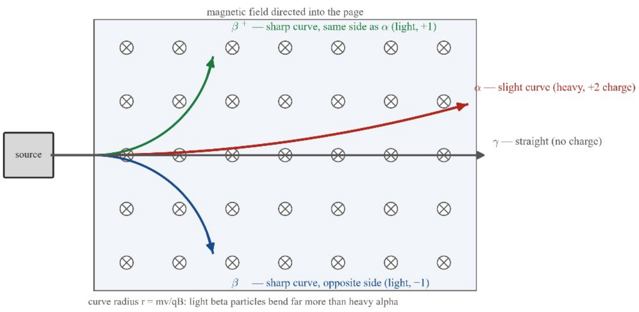
A note on neutrinos. A complete description of beta decay includes one further particle. In β^- decay an **antineutrino** is also emitted; in β^+ decay a **neutrino** is emitted. These particles have no charge and an extraordinarily small mass, interact with matter so weakly that they almost always pass straight through the Earth, and were proposed in 1930 precisely to account for the energy shared with the beta particle. Because a neutrino carries no charge and contributes nothing to the mass number, it does not affect the balancing of a decay equation, and the equations in this course are written without it. Neutrinos reappear in Option 2.17, where their prediction and detection are part of the story of how matter came to be.

Comparing the three radiations.

Property	α	β⁻	β⁺	γ
Nature	helium-4 nucleus (2 p + 2 n)	electron	positron	electromagnetic radiation
Symbol	${}^{4}_{2}\text{He}$	${}^{0}_{-1}\text{e}$	${}^{0}_{+1}\text{e}$	γ
Charge	$+2e$ ($+3.2\times10^{-19}$ C)	$-e$ (-1.6×10^{-19} C)	$+e$ ($+1.6\times10^{-19}$ C)	0
Mass	≈ 4 nucleon masses (≈ 7000 electron masses)	$\approx \frac{1}{1840}$ of a proton	same as β⁻	0
Typical speed	$\approx 5\%$ of c	up to $\approx 99\%$ of c	up to $\approx 99\%$ of c	c
Ionising power	very strong	moderate	moderate	weak
Range in air	a few centimetres	up to about a metre	up to about a metre, then annihilation	very long
Stopped by	sheet of paper; dead outer skin	a few millimetres of aluminium	a few millimetres of aluminium (then annihilates)	reduced by thick lead or concrete, never completely
Change to the nucleus	A falls by 4, Z falls by 2	A unchanged, Z rises by 1	A unchanged, Z falls by 1	no change to A or Z



The radiations are also distinguished by their behaviour in a magnetic field. A charged particle moving through a magnetic field experiences a force at right angles to its motion, so its path curves. Alpha particles, being positive, curve one way — but only slightly, because their large mass makes them hard to deflect. Beta-minus particles, being negative, curve the opposite way, and sharply, because they are so light. Positrons curve the same way as alpha particles, but sharply, for the same reason. Gamma rays, having no charge, are not deflected at all and continue in a straight line.



Worked examples

Example 1 — scaffolded

Radium-226 was used in the early 1900s to make luminous paint for watch dials and aircraft instruments. It decays by alpha emission. Complete the decay equation, identifying the daughter nucleus.

Working	Comment
Radium has atomic number 88. Parent: $^{226}_{88}\mathrm{Ra}$. Alpha particle: $^{4}_{2}\mathrm{He}$ on the right side.	Set up the equation: $^{226}_{88}\mathrm{Ra} \rightarrow {}^{A}_{Z}Y + {}^{4}_{2}\mathrm{He}$.
Top numbers: $226 = A + 4$, so $A = 222$.	Mass number is conserved.
Bottom numbers: $88 = Z + 2$, so $Z = 86$.	Charge is conserved.
$Z = 86$ is radon, Rn.	The atomic number fixes the element.
$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}$. Check: tops $226 = 222 + 4$ ✓, bottoms $88 = 86 + 2$ ✓.	The daughter is radon-222, a radioactive gas.

Example 2 — scaffolded

Strontium-90 is one of the radioisotopes produced when uranium undergoes fission in a nuclear reactor, and it is carefully monitored in the environment around nuclear sites. It decays by beta-minus emission. Complete the decay equation, identifying the daughter nucleus.

Working	Comment
Strontium has atomic number 38. Parent: $^{90}_{38}\mathrm{Sr}$. Beta-minus particle: $^{0}_{-1}\mathrm{e}$ on the right side.	Set up: $^{90}_{38}\mathrm{Sr} \rightarrow {}^{A}_{Z}Y + {}^{0}_{-1}\mathrm{e}$.
Top numbers: $90 = A + 0$, so $A = 90$.	The emitted electron contributes no nucleons.
Bottom numbers: $38 = Z + (-1)$, so $Z = 39$.	A neutron has changed into a proton, so the proton count rises by one.
$Z = 39$ is yttrium, Y.	The daughter is one place higher in the periodic table than the parent.
$^{90}_{38}\mathrm{Sr} \rightarrow {}^{90}_{39}\mathrm{Y} + {}^{0}_{-1}\mathrm{e}$. Check: tops $90 = 90 + 0$ ✓, bottoms $38 = 39 - 1$ ✓.	The daughter is yttrium-90.

Example 3 — unscaffolded

Fluorine-18 is a positron-emitting radioisotope made in hospitals for PET (positron emission tomography) scans; the imaging technique that uses it is treated in Option 2.6. Write the decay equation for fluorine-18, identify the daughter nucleus, and state what happens to the emitted positron soon afterwards.

Fluorine has atomic number 9, so the parent is $^{18}_{9}\mathrm{F}$, and a beta-plus decay emits $^{0}_{+1}\mathrm{e}$. Mass number is conserved, so the daughter has $A = 18$; charge is conserved, so the daughter has $Z = 9 - 1 = 8$, which is oxygen: $^{18}_{9}\mathrm{F} \rightarrow {}^{18}_{8}\mathrm{O} + {}^{0}_{+1}\mathrm{e}$ (Check: tops $18 = 18 + 0$ ✓; bottoms $9 = 8 + 1$ ✓.)

∴ the daughter nucleus is oxygen-18. Within a very short distance of where it was emitted, the positron meets an electron, and the two annihilate: both particles disappear and their energy is carried away by two gamma rays travelling in opposite directions.

Example 4 — unscaffolded

The decay of uranium-238 begins a long chain of decays that is analysed in 3D. The first three steps are:

$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + P_1$ $^{234}_{90}\mathrm{Th} \rightarrow {}^{234}_{91}\mathrm{Pa} + P_2$ $^{234}_{91}\mathrm{Pa} \rightarrow {}^{234}_{92}\mathrm{U} + P_3$

Identify each emitted particle P_1, P_2 and P_3, and name the type of decay in each step.

In the first step, the mass number falls by 4 (238 → 234) and the atomic number falls by 2 (92 → 90), so P_1 carries $A = 4$ and $Z = 2$: it is $^{4}_{2}\mathrm{He}$, an alpha particle, and the step is **alpha decay**.

In the second step, A is unchanged and Z rises by 1 (90 → 91), so P_2 carries $A = 0$ and $Z = -1$: it is ${}^{0}_{-1}e$, a beta-minus particle, and the step is **beta-minus decay** (a neutron has changed into a proton).

In the third step, A is again unchanged and Z rises by 1 (91 → 92), so P_3 is likewise ${}^{0}_{-1}e$: a second **beta-minus decay**.

∴ $P_1 = {}^{4}_{2}He$ (alpha decay), $P_2 = {}^{0}_{-1}e$ (beta-minus decay), $P_3 = {}^{0}_{-1}e$ (beta-minus decay). After one alpha decay and two beta-minus decays, the nucleus is once again uranium — but uranium-234, a different isotope from the uranium-238 we began with.

Practice questions

Question 1 Copy and complete the table below, which compares the three main types of nuclear radiation.

Property	α	β^-	γ
Nature	(a) …	electron	(b) …
Charge	(c) …	(d) …	(e) …
Stopped by	(f) …	a few millimetres of aluminium	(g) …
Ionising power	very strong	(h) …	(i) …

Question 2 Polonium-210 and americium-241 both decay by alpha emission. Americium-241 is the isotope used as the radiation source in many household ionisation smoke detectors. Write the complete decay equation for each isotope, identifying the daughter nucleus in each case.

Question 3 Potassium-40 decays by beta-minus emission to calcium-40. Tritium (hydrogen-3) also decays by beta-minus emission, to helium-3. (a) Write the decay equation for potassium-40. (b) Write the decay equation for tritium. (c) State what happens to the number of protons and the number of neutrons in each nucleus during these decays.

Question 4 Carbon-11 and sodium-22 both decay by beta-plus (positron) emission. (a) Write the decay equation for carbon-11. (b) Write the decay equation for sodium-22. (c) State the mass number and the charge of the emitted positron.

Question 5 Technetium-99m, written ${}^{99m}_{43}Tc$, is the radioisotope most commonly used in medical imaging. The “m” marks a nucleus in an excited state. The nucleus releases its excess energy by emitting a single gamma ray. (a) Write the decay equation. (b) State the mass number and atomic number of the daughter nucleus. (c) Explain why gamma emission does not change one element into another.

Question 6 A laboratory has three sealed sources: one emits only alpha radiation, one emits only beta-minus radiation and one emits only gamma radiation. The laboratory has sheets of paper, blocks of aluminium and blocks of lead. (a) Match each type of radiation with the material that would be used to shield it. (b) Justify each match using the penetrating properties of the radiations.

Question 7 Radon-222 is a radioactive gas formed naturally in rocks. It decays to polonium-218 by emitting one particle. Complete the equation ${}^{222}_{86}Rn \rightarrow {}^{218}_{84}Po + ?$ and name the type of decay.

Question 8 Iodine-131 is a radioisotope produced in nuclear reactors. Write the complete equation for its beta-minus decay to xenon-131. (Iodine has $Z = 53$; xenon has $Z = 54$.)

Question 9 A nucleus decays by alpha emission, producing thorium-234 as the daughter: $? \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$. Identify the parent nucleus.

Question 10 In each case identify the missing particle and name the type of decay. (a) ${}^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + ?$ (b) ${}^{210}_{83}Bi \rightarrow {}^{210}_{84}Po + ?$

Question 11 When a beam containing α, β^- and γ radiation passes through a magnetic field, the three radiations follow different paths. Explain why the alpha particles are deflected only slightly, why the beta-minus particles are deflected strongly, and why the two are deflected in opposite directions.

Question 12 Alpha radiation is the most strongly ionising of the three radiations, yet it is the least penetrating. Explain why these two facts are connected, rather than contradictory.

Question 13 Explain why a nucleus that emits a gamma ray keeps the same mass number and the same atomic number.

Question 14 Explain, in terms of what happens to one of its nucleons, why a nucleus that undergoes beta-minus decay ends up with an atomic number one greater than it started with.

Question 15 Explain what happens to a positron a short time after it is emitted in beta-plus decay, and identify the radiation produced.

Question 16 Many household smoke detectors contain a tiny amount of americium-241, an alpha emitter. The radiation ionises the air inside the detector, and the detector alarms when smoke interferes with this ionisation. (a) Explain why an alpha source is suited to ionising the air inside the detector, rather than a beta or gamma source. (b) Explain, using the penetrating properties of alpha radiation, why the radiation does not leave the detector in significant amounts.

Question 17 Cobalt-60 is a radioisotope whose gamma radiation is used to sterilise medical equipment. Cobalt-60 first decays by beta-minus emission to an excited nickel-60 nucleus, which then emits a gamma ray. Cobalt has $Z = 27$; nickel has $Z = 28$. (a) Write the beta-minus decay equation. (b) Write the gamma emission equation.

Question 18 A soft-drink factory checks that sealed aluminium cans are filled to the top by placing a radioactive source on one side of each can and a detector on the other. (a) Explain why a gamma source is used for this job rather than an alpha source or a beta-minus source. (b) State and explain how the reading on the detector differs between a full can and an underfilled can.

Question 19 A student says: "Because gamma radiation is the most penetrating, it must ionise matter more strongly than alpha or beta radiation." Explain why this reasoning does not follow, referring to the penetrating and ionising powers of the three radiations and the connection between them.

Question 20 Thorium-232 decays by alpha emission, and the daughter then undergoes two successive beta-minus decays. Determine the final nucleus produced, showing each step, and explain how the element can end up being thorium again even though three decays have occurred.

Question 21 A student writes the beta decay of carbon-14 as ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{+1}e$. Identify what is wrong with this equation and write the correct equation.

Answers

Question 1 (a) helium-4 nucleus; (b) electromagnetic radiation; (c) $+2e$; (d) $-e$; (e) 0; (f) sheet of paper (or a few centimetres of air); (g) thick lead or concrete (reduced, never completely stopped); (h) moderate; (i) weak. **Question 2** ${}^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$ (lead-206); ${}^{241}_{95}\mathrm{Am} \rightarrow {}^{237}_{93}\mathrm{Np} + {}^{4}_{2}\mathrm{He}$ (neptunium-237). **Question 3** (a) ${}^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{20}\mathrm{Ca} + {}^{0}_{-1}\mathrm{e}$; (b) ${}^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{-1}\mathrm{e}$; (c) one neutron becomes one proton: neutron number falls by 1, proton number rises by 1. **Question 4** (a) ${}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{+1}\mathrm{e}$; (b) ${}^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{0}_{+1}\mathrm{e}$; (c) mass number 0, charge $+1e$ ($+1.6\times10^{-19}$ C). **Question 5** (a) ${}^{99m}_{43}\mathrm{Tc} \rightarrow {}^{99}_{43}\mathrm{Tc} + \gamma$; (b) $A=99$, $Z=43$; (c) no proton or neutron leaves the nucleus — only energy is released. **Question 6** (a) alpha — paper; beta-minus — aluminium; gamma — lead; (b) each shield is matched to the radiation's penetrating power: alpha is stopped by paper, beta by a few millimetres of aluminium, and gamma is best reduced by dense lead. **Question 7** ${}^{4}_{2}\mathrm{He}$; alpha decay. **Question 8** ${}^{131}_{53}\mathrm{I} \rightarrow {}^{131}_{54}\mathrm{Xe} + {}^{0}_{-1}\mathrm{e}$. **Question 9** ${}^{238}_{92}\mathrm{U}$, uranium-238. **Question 10** (a) ${}^{0}_{+1}\mathrm{e}$, beta-plus decay; (b) ${}^{0}_{-1}\mathrm{e}$, beta-minus decay. **Question 11** Alpha particles are positive but very massive, so the magnetic force produces only a small deflection; beta-minus particles are negative and about 7000 times lighter, so they curve sharply; opposite charges experience forces in opposite directions. **Question 12** Because alpha particles ionise so strongly, they transfer their energy to the material over a very short distance, so they are stopped quickly. **Question 13** A gamma ray carries energy only — no protons or neutrons leave the nucleus, so A and Z are unchanged. **Question 14** A neutron changes into a proton, emitting an electron; the proton number rises by one, and the atomic number is the proton number. **Question 15** It meets an electron and the two annihilate, producing two gamma rays travelling in opposite directions. **Question 16** (a) Alpha radiation is the most strongly ionising, so it ionises the air between the detector's parts effectively; (b) alpha particles are stopped by a few centimetres of air and by the detector's plastic casing. **Question 17** (a) ${}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni}^* + {}^{0}_{-1}\mathrm{e}$; (b) ${}^{60}_{28}\mathrm{Ni}^* \rightarrow {}^{60}_{28}\mathrm{Ni} + \gamma$. **Question 18** (a) Gamma radiation penetrates the aluminium and the drink; alpha would be stopped by the can wall and beta by the liquid; (b) a full can absorbs more of the gamma radiation, so the detector reading is lower for a full can than for an underfilled one. **Question 19** Penetrating power and ionising power are not the same property; gamma is the least ionising radiation, and weak ionisation is precisely why it keeps its energy over long distances. **Question 20** ${}^{232}_{90}\mathrm{Th} \rightarrow {}^{228}_{88}\mathrm{Ra} + {}^{4}_{2}\mathrm{He}$, then ${}^{228}_{88}\mathrm{Ra} \rightarrow {}^{228}_{89}\mathrm{Ac} + {}^{0}_{-1}\mathrm{e}$, then ${}^{228}_{89}\mathrm{Ac} \rightarrow {}^{228}_{90}\mathrm{Th} + {}^{0}_{-1}\mathrm{e}$; the final nucleus is thorium-228 — the alpha decay lowered Z by 2 and the two beta decays restored it by 1 each. **Question 21** Charge is not conserved: $6 \neq 7+1$. The emitted particle must be ${}^{0}_{-1}\mathrm{e}$: ${}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}$.

Fully-worked solutions

Question 1 The comparison of the three radiations:

Property	α	β^-	γ
Nature	helium-4 nucleus (2 protons + 2 neutrons)	electron	electromagnetic radiation
Charge	$+2e$ ($+3.2\times10^{-19}$ C)	$-e$ (-1.6×10^{-19} C)	0
Stopped by	sheet of paper; a few centimetres of air	a few millimetres of aluminium	reduced by thick lead or concrete; never completely stopped
Ionising power	very strong	moderate	weak

Question 2 Alpha emission removes 4 from the mass number and 2 from the atomic number. Polonium has $Z=84$: ${}^{210}_{84}\mathrm{Po} \rightarrow {}^{A}_{Z}Y + {}^{4}_{2}\mathrm{He}$ gives $A=210-4=206$ and $Z=84-2=82$, which is lead: ${}^{210}_{84}\mathrm{Po} \rightarrow {}^{206}_{82}\mathrm{Pb} + {}^{4}_{2}\mathrm{He}$ Americium has $Z=95$: $A=241-4=237$, $Z=95-2=93$, which is neptunium: ${}^{241}_{95}\mathrm{Am} \rightarrow {}^{237}_{93}\mathrm{Np} + {}^{4}_{2}\mathrm{He}$

Question 3 In beta-minus decay a neutron becomes a proton, so A is unchanged and Z rises by 1. (a) Potassium has $Z=19$ and calcium has $Z=20$: ${}^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{20}\mathrm{Ca} + {}^{0}_{-1}\mathrm{e}$ (check: tops $40=40+0$ ✓, bottoms $19=20-1$ ✓). (b) Hydrogen has $Z=1$ and helium has $Z=2$: ${}^{3}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{0}_{-1}\mathrm{e}$ (check: tops $3=3+0$ ✓, bottoms $1=2-1$ ✓). (c) In each nucleus, one neutron has changed into one proton: the neutron number decreases by 1 and the proton number increases by 1, so the mass number (protons + neutrons) stays the same.

Question 4 In beta-plus decay a proton becomes a neutron, so A is unchanged and Z falls by 1. (a) Carbon has $Z = 6$ and boron has $Z = 5$: ${}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{+1}\mathrm{e}$. (b) Sodium has $Z = 11$ and neon has $Z = 10$: ${}^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{0}_{+1}\mathrm{e}$. (c) The positron is written ${}^{0}_{+1}\mathrm{e}$: mass number 0 and charge $+1\,e = +1.6 \times 10^{-19}\,\mathrm{C}$.

Question 5 (a) Gamma emission releases energy only, so the nucleus keeps its A and Z: ${}^{99\mathrm{m}}_{43}\mathrm{Tc} \rightarrow {}^{99}_{43}\mathrm{Tc} + \gamma$ (b) The daughter is technetium-99 with mass number $A = 99$ and atomic number $Z = 43$ — the same element, in a lower-energy state. (c) The identity of an element is fixed by its atomic number, the number of protons. In gamma emission no proton or neutron leaves the nucleus; the nucleus only loses excess energy. Since Z is unchanged, the element is unchanged.

Question 6 (a) Alpha — paper; beta-minus — aluminium; gamma — lead. (b) Alpha radiation is the least penetrating: it is stopped by a sheet of paper (or a few centimetres of air), so paper is a sufficient and practical shield. Beta-minus radiation passes through paper but is absorbed by a few millimetres of aluminium. Gamma radiation passes through both paper and aluminium; it is only *reduced*, never completely stopped, and dense lead is the practical material for reducing it substantially.

Question 7 The mass number falls by 4 $(222 - 218)$ and the atomic number by 2 $(86 - 84)$, so the emitted particle carries $A = 4$ and $Z = 2$: ${}^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + {}^{4}_{2}\mathrm{He}$ The particle is an alpha particle, and the decay is **alpha decay**.

Question 8 In beta-minus decay A is unchanged and Z rises by 1. With iodine $Z = 53$ and xenon $Z = 54$: ${}^{131}_{53}\mathrm{I} \rightarrow {}^{131}_{54}\mathrm{Xe} + {}^{0}_{-1}\mathrm{e}$ Check: tops $131 = 131 + 0$ ✓; bottoms $53 = 54 - 1$ ✓.

Question 9 Work backwards from the conservation rules. The parent's mass number is the sum of the top numbers on the right: $A = 234 + 4 = 238$. The parent's atomic number is the sum of the bottom numbers: $Z = 90 + 2 = 92$. The element with $Z = 92$ is uranium, so the parent is ${}^{238}_{92}\mathrm{U}$ (uranium-238).

Question 10 (a) A is unchanged $(22 = 22 + 0)$ and Z falls by 1 $(11 = 10 + 1)$, so the particle is ${}^{0}_{+1}\mathrm{e}$, a positron: this is **beta-plus decay**. (b) A is unchanged $(210 = 210 + 0)$ and Z rises by 1 $(83 = 84 - 1)$, so the particle is ${}^{0}_{-1}\mathrm{e}$, an electron: this is **beta-minus decay**.

Question 11 A charged particle moving through a magnetic field experiences a force at right angles to its motion, so its path curves. The direction of the force depends on the sign of the charge: alpha particles have charge $+2e$ and beta-minus particles have charge $-e$, so the forces on them act in opposite directions and they curve opposite ways. The amount of deflection depends on the mass: an alpha particle is about 7000 times more massive than an electron, so the same kind of force changes its motion only slightly, while the light electron is bent into a tight curve. Gamma rays carry no charge, so they feel no magnetic force and are not deflected at all.

Question 12 The two facts are two sides of the one behaviour. An alpha particle's double charge and low speed make it interact strongly with the atoms it passes, stripping electrons from them — that is ionisation. Every ionisation takes energy from the alpha particle, so its energy is used up over a very short distance: a few centimetres of air or a sheet of paper. Strong ionisation means rapid energy loss, and rapid energy loss means short range. The radiations that ionise less strongly (beta, gamma) keep their energy over longer distances and so penetrate further.

Question 13 A gamma ray is electromagnetic radiation — energy carried away from the nucleus — not a particle made of nucleons. In gamma emission no proton and no neutron leaves the nucleus, so the mass number A (total nucleons) and the atomic number Z (protons) are both unchanged. The nucleus simply drops from an excited state to a lower-energy state.

Question 14 In beta-minus decay one of the nucleus's neutrons changes into a proton, and an electron (the beta particle) is created and emitted at the same instant. The nucleus therefore contains one more proton than before. Since the atomic number is defined as the number of protons, the atomic number increases by 1 — and the nucleus becomes a different element, one place higher in the periodic table.

Question 15 The positron is the antimatter partner of the electron. After travelling only a short distance through matter it encounters an electron, and the two annihilate: both particles disappear, and their energy is carried away by two gamma rays. The two gamma rays travel in opposite directions — this back-to-back emission is what PET scanners detect (Option 2.6).

Question 16 (a) Alpha radiation is the most strongly ionising of the three radiations, because alpha particles carry charge $+2e$ and move relatively slowly, so they interact strongly with the air molecules they pass. This is exactly what the detector needs: a steady supply of ions in the air between its parts. Beta and gamma sources ionise the air far less strongly, so they would produce a much weaker effect. (b) Alpha particles have a range of only a few centimetres in air and are stopped by a sheet of paper, so the air gap inside the detector and the detector's own plastic casing absorb them. Very little alpha radiation can escape the sealed unit.

Question 17 (a) Beta-minus emission leaves $A=60$ unchanged and raises Z from 27 to 28, giving nickel-60 in an excited state: ${}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni}^* + {}^{0}_{-1}\mathrm{e}$ (b) The excited nickel nucleus then drops to a lower-energy state by emitting a gamma ray, with no change of element: ${}^{60}_{28}\mathrm{Ni}^* \rightarrow {}^{60}_{28}\mathrm{Ni} + \gamma$ It is these penetrating gamma rays that are used to sterilise sealed medical equipment, because they reach through the packaging to the equipment inside.

Question 18 (a) The radiation must pass through aluminium and through liquid to reach the detector on the far side. Alpha radiation would be stopped by the can wall alone, and beta-minus radiation would be absorbed by the wall and the liquid; gamma radiation is penetrating enough that a measurable amount reaches the detector, with the amount depending on how much liquid is in the way. (b) A full can places more liquid between the source and the detector, so more of the gamma radiation is absorbed and the detector reading is lower. An underfilled can has an air gap above the liquid; gamma radiation passes through air with little absorption, so the reading is higher when the beam passes above the fill level.

Question 19 The reasoning confuses two different properties: penetrating power (how far the radiation travels before being absorbed) and ionising power (how strongly it strips electrons from the atoms it passes). The two are connected in the *opposite* way to the student's claim. Alpha radiation is the most strongly ionising precisely because its particles interact so strongly with matter — and that strong interaction is why they lose their energy over a few centimetres and penetrate least. Gamma radiation is the weakest ioniser; because it interacts so rarely, it keeps its energy over long distances and penetrates furthest. Beta radiation is in between on both counts. So "most penetrating" corresponds to *least* ionising, not most. (How these properties translate into effects on humans, including what happens when a source is outside or inside the body, is taken up in 3E.)

Question 20 Step 1, alpha decay: A falls by 4 and Z falls by 2: ${}^{232}_{90}\mathrm{Th} \rightarrow {}^{228}_{88}\mathrm{Ra} + {}^{4}_{2}\mathrm{He}$ Step 2, beta-minus decay: A is unchanged and Z rises by 1: ${}^{228}_{88}\mathrm{Ra} \rightarrow {}^{228}_{89}\mathrm{Ac} + {}^{0}_{-1}\mathrm{e}$ Step 3, beta-minus decay again: ${}^{228}_{89}\mathrm{Ac} \rightarrow {}^{228}_{90}\mathrm{Th} + {}^{0}_{-1}\mathrm{e}$ The final nucleus is **thorium-228**. The element returns to thorium because the three decays change Z by -2, then $+1$, then $+1$: the alpha decay moved the nucleus two places down the periodic table, and the two beta-minus decays — each converting a neutron into a proton — moved it back one place each. The mass number, however, has fallen from 232 to 228, so the final thorium is a different isotope from the one we began with.

Question 21 Check the two conservation rules. Mass number: $14=14+0$ ✓. Charge: 6 on the left, but $7+1=8$ on the right ✗ — charge is not conserved, so the equation cannot be correct. Carbon-14 decays by beta-minus emission (its atomic number rises from 6 to 7), so the emitted particle must carry charge -1, not $+1$. The correct equation is ${}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\mathrm{e}$ with bottoms $6=7-1$ ✓. The student's equation would describe beta-plus decay — but in that case the daughter's atomic number would have to fall, not rise.

Chapter 3 Radiation from the nucleus — 3C Half-life and modelling radioactive decay

Theory

In 3A you saw that some nuclei are unstable, and in 3B you wrote decay equations showing what an unstable nucleus gives out when it decays. This section asks a different question: **when** do nuclei decay, and **how much** of a sample is left at a later time?

Decay is random. The decay of any single nucleus is completely random. It is impossible to say which nucleus in a sample will decay next, or when any particular nucleus will decay, and nothing you can do to the sample — heat it, cool it, place it under pressure — will change this. Every undecayed nucleus of a given isotope has the same fixed chance of decaying in a given time interval. One nucleus is unpredictable, but a sample contains an enormous number of nuclei, and the *average* behaviour of a large number of random events is very predictable: in any fixed time interval, the same **fraction** of the undecayed nuclei will decay. This is what makes radioactive decay possible to model mathematically.

Half-life. Because the same fraction of the undecayed nuclei decays in each equal time interval, the number of undecayed nuclei falls by a constant factor over a time that is characteristic of the isotope. The **half-life**, $t_{1/2}$, of a radioisotope is the time taken for half of the undecayed nuclei in a sample to decay. Equivalently, it is the time for the sample's **activity** — the number of decays per second, measured in **becquerels** (Bq, where $1\,\mathrm{Bq} = 1$ decay per second) — to fall to half its starting value, or the time for the count rate recorded by a detector such as a Geiger–Müller counter to halve.

Every radioactive isotope (radioisotope) has its own characteristic half-life, ranging from far less than a second to billions of years. The half-life of a given isotope is constant: it does not depend on the size of the sample, its temperature, or what the isotope is chemically combined with. Some half-lives you will meet in this chapter and the next are listed below.

Isotope	Half-life
radon-222	3.8 days
technetium-99m	6.0 hours
iodine-131	8.0 days
cobalt-60	5.27 years
strontium-90	28.8 years
caesium-137	30 years
carbon-14	5730 years

Source: IAEA Nuclear Data Section, LiveChart of Nuclides, retrieved 2026-08-18.

Modelling decay with whole half-lives. If a sample starts with N_0 undecayed nuclei, then after one half-life $\frac{1}{2}N_0$ remain, after two half-lives $\frac{1}{4}N_0$ remain, and so on — the number remaining is halved once for every half-life that passes.

Half-lives elapsed, n	Fraction of nuclei remaining
0	1
1	$\frac{1}{2}$
2	$\frac{1}{4}$

Half-lives elapsed, n	Fraction of nuclei remaining
3	$\frac{1}{8}$
4	$\frac{1}{16}$
5	$\frac{1}{32}$

This gives the model

$$N = N_0 \left(\frac{1}{2}\right)^n, n = \frac{t}{t_{1/2}},$$

where n is the number of whole half-lives that have elapsed. The same halving rule applies to the activity and to the mass of undecayed isotope, not just to the number of nuclei. The fraction of the original nuclei that **have decayed** after n half-lives is $1 - \left(\frac{1}{2}\right)^n$ — after two half-lives, $\frac{3}{4}$ of the sample has decayed, not all of it. In this unit the mathematical modelling is restricted to times that are whole numbers of half-lives.

Decay curves. Plotting the number of undecayed nuclei, or the activity, against time gives the characteristic decay curve: it falls steeply at first and then flattens out, dropping by half over every equal time interval. In the model the curve never reaches zero — there is always half of the previous amount left after each further half-life.

To find a half-life from a decay curve or a data table, choose any value of the activity (or number remaining) and read off the time at which it occurs, then find the time at which the value has fallen to half of it. The time difference is one half-life. Check your answer using a second pair of values: if the time is the same, the half-life is constant, as the model requires.

Modelling decay with a simulation. Because real decay happens inside nuclei you cannot see, radioactive decay is often modelled with a simulation. A common version uses coins or dice:

- each coin (or die) represents one undecayed nucleus;
- each throw represents one equal time interval;
- on each throw, coins landing heads (or dice showing a chosen number) have "decayed" and are removed.

Each individual throw is random, but the chance of "decay" is the same on every throw, so the number of coins remaining falls by about half each throw — the simulation produces the same halving pattern, and the same kind of decay curve, as a real radioactive sample. Like every model, it has limitations: a handful of coins is a very small "sample", so the results are much bumpier than real decay; the chance of decay is fixed by the coin (one in two) or the die (one in six) rather than by the isotope; and time advances in jumps of one throw. Using more coins, or combining the results of the whole class, makes the model's behaviour smoother and closer to a real sample.

Half-life is not just a number to calculate with. It tells a hospital how long a medical radioisotope remains active enough to be useful and how quickly it fades from the patient's body (3F, and Option 2.6 in 10E), and it tells physicists how long a radioactive source or waste remains active enough to need careful handling (3E).

Worked examples

Example 1 — scaffolded

A freshly prepared sample of iodine-131 (half-life 8.0 days) gives a count rate of $800 \text{ counts min}^{-1}$. Calculate the count rate from the sample after 24 days.

Working	Comment
$t_{1/2} = 8.0$ days; starting count rate $= 800 \text{ counts min}^{-1}$.	List the data. The count rate is proportional to the

Working	Comment
	activity, so it halves each half-life.
$n=\frac{t}{t_{1/2}}=\frac{24}{8.0}=3$	Find the number of whole half-lives in 24 days.
Count rate $=800\times\left(\frac{1}{2}\right)^3=800\times\frac{1}{8}=100\,\text{counts min}^{-1}$.	Halve the count rate three times: $800\rightarrow400\rightarrow200\rightarrow100$.

Example 2 — scaffolded

A student measures the count rate from a sample of technetium-99m every 6.0 hours, with the results below. (a) Determine the half-life of technetium-99m. (b) Predict the count rate at 24 hours.

Time (hours)	0	6.0	12.0	18.0
Count rate (counts s^{-1})	640	320	160	80

Working	Comment
Compare successive readings: $640\rightarrow320\rightarrow160\rightarrow80$.	Each reading is exactly half the one before it.
The count rate halves every 6.0 hours, so $t_{1/2}=6.0$ hours.	The half-life is the time for the count rate to fall to half its value; check that it is the same for every interval.
At 24 hours one more half-life has passed: $80\rightarrow40\,\text{counts s}^{-1}$.	Extend the halving pattern by one further half-life.

Example 3 — unscaffolded

Cobalt-60, half-life 5.27 years, is used as a source of γ radiation in cancer treatment. A source contains 4.0×10^{18} undecayed cobalt-60 nuclei. Calculate the number of undecayed nuclei remaining after 15.81 years, and the fraction of the original nuclei that have decayed in that time.

The number of whole half-lives elapsed is

$$n=\frac{t}{t_{1/2}}=\frac{15.81}{5.27}=3.$$

Applying the halving model,

$$N=N_0\left(\frac{1}{2}\right)^n=4.0\times10^{18}\times\left(\frac{1}{2}\right)^3=4.0\times10^{18}\times\frac{1}{8}=5.0\times10^{17}.$$

Only $\frac{1}{8}$ of the nuclei remain, so the fraction that have decayed is the rest:

$$1-\left(\frac{1}{2}\right)^3=1-\frac{1}{8}=\frac{7}{8}.$$

$\therefore$ 5.0×10^{17} nuclei remain undecayed, and $\frac{7}{8}$ of the original nuclei have decayed.

Example 4 — unscaffolded

A group of students model radioactive decay using 64 coins. Each coin represents one nucleus; on each throw, coins that land heads have decayed and are removed. The table shows the number of coins remaining after each throw.

Throw	0 (start)	1	2	3	4
Expected	64	32	16	8	4

Throw	0 (start)	1	2	3	4
number remaining					
One group’s result	64	30	17	7	4

Since each coin has a one-in-two chance of landing heads, about half the coins are removed on every throw, so the expected number remaining halves each throw and the half-life of this model is one throw. The group’s actual result differs from the expected values at every step — 30 rather than 32, then 17 rather than 16 — because each coin lands randomly: the model predicts the *average* behaviour, not any single run. Notice, though, that both rows fall by roughly half each throw, so the simulation still shows the essential feature of radioactive decay — random events producing a predictable halving pattern. To bring the results closer to the expected values, the class could use many more coins or combine every group’s results, just as a real sample’s enormous number of nuclei makes its decay smooth and predictable.

Practice questions

Question 1 A sealed container holds radon-222, half-life 3.8 days, with an initial activity of $1200\,\text{Bq}$. (a) State what is meant by the half-life of a radioisotope. (b) Calculate the activity after 3.8 days. (c) Calculate the activity after 11.4 days. (d) Determine the fraction of the original nuclei that have decayed after 11.4 days.

Question 2 A student measures the count rate from a sample of an unknown radioisotope every 5.0 minutes.

Time (min)	0	5.0	10.0	15.0	20.0
Count rate (counts min^{-1})	480	240	120	60	30

(a) State the half-life of the isotope.
(b) Predict the count rate at 25 minutes.
(c) Determine the time at which the count rate will be $7.5\,\text{counts min}^{-1}$.

Question 3 A hospital radiology department prepares a dose of technetium-99m, half-life 6.0 hours, with an initial activity of $900\,\text{MBq}$ ($1\,\text{MBq} = 10^6\,\text{Bq}$). (a) Calculate the number of half-lives that elapse in 24 hours. (b) State the fraction of the original activity remaining after 24 hours. (c) Calculate the activity of the dose 24 hours after it was prepared.

Question 4 A sample contains 1.6×10^{13} undecayed nuclei of a radioisotope with a half-life of 20 minutes. (a) Calculate the number of undecayed nuclei remaining after 60 minutes. (b) Calculate the number of nuclei that have decayed in that time. (c) Determine the time at which 1.0×10^{12} undecayed nuclei remain.

Question 5 A class models radioactive decay with 32 coins. Each coin represents one nucleus, and coins that land heads are removed after each throw. (a) Copy and complete the table of the expected number of coins remaining.

Throw	0 (start)	1	2	3	4
Expected number remaining	32				

(b) One group’s results were 14, 9, 4, 2, 1 remaining after throws 1 to 4. Explain why these results differ from the expected values.
(c) Suggest one way the class could make their results closer to the expected values, and justify your suggestion.

Question 6 A sample has an activity of $800\,\text{Bq}$ at time zero, and a half-life of 10 minutes. (a) Copy and complete the table of the sample’s activity.

Time (min)	0	10	20	30	40
Activity (Bq)	800				

(b) On a set of axes of activity against time, plot the values from your table and draw a smooth curve through them.

(c) Use your curve to determine the time at which the activity is $25\,\mathrm{Bq}$.

Question 7 Iodine-131 has a half-life of 8.0 days. A sample has an initial activity of $400\,\mathrm{MBq}$. Calculate the activity of the sample after 32 days.

Question 8 Caesium-137, a product of nuclear fission, has a half-life of 30 years. Determine the time taken for the activity of a caesium-137 sample to fall to $\frac{1}{16}$ of its initial value.

Question 9 The count rate from a sample of a radioisotope falls from $360\,\text{counts min}^{-1}$ to $45\,\text{counts min}^{-1}$ over 45 minutes. Determine the half-life of the isotope.

Question 10 Sodium-24 has a half-life of 15 hours. A sample initially contains $8.0\,\mu\mathrm{g}$ of sodium-24. Calculate the mass of undecayed sodium-24 remaining after 45 hours.

Question 11 Determine the fraction, and the percentage, of a radioactive sample that remains undecayed after five half-lives.

Question 12 Two samples, X and Y, start with the same activity. Isotope X has a half-life of 2.0 days and isotope Y has a half-life of 8.0 days. Determine the ratio of the activity of sample X to the activity of sample Y after 8.0 days.

Question 13 Radioactive decay is described as random. Explain what this means for a single nucleus, and why physicists can nevertheless make accurate predictions about a whole sample.

Question 14 A student says: “After one half-life, half the nuclei have decayed, and after the second half-life the other half decay, so after two half-lives the sample is completely gone.” Identify the error in this reasoning and state the fraction of the sample that actually remains after two half-lives.

Question 15 Two samples of the same radioisotope are prepared, one containing twice as many undecayed nuclei as the other. Compare the half-lives of the two samples and explain your answer.

Question 16 Technetium-99m, half-life 6.0 hours, is widely used for medical scans that take several hours to complete. Justify why an isotope with a half-life of 6.0 hours is a better choice for this purpose than an isotope with a half-life of 6.0 years.

Question 17 The halving model predicts that a sample’s activity falls by half over and over but never reaches zero. Explain why a real sample nevertheless eventually contains no undecayed nuclei at all.

Question 18 Evaluate the coin model of radioactive decay used in Question 5: state two ways in which it represents real radioactive decay well, and two limitations of the model.

Answers

Question 1 (a) the time taken for half of the undecayed nuclei in a sample to decay (equivalently, for the activity to halve); (b) $600\,\mathrm{Bq}$; (c) $150\,\mathrm{Bq}$; (d) $\frac{7}{8}$. **Question 2** (a) 5.0 minutes; (b) $15\,\text{counts min}^{-1}$; (c) 30 minutes. **Question 3** (a) 4; (b) $\frac{1}{16}$; (c) $56\,\mathrm{MBq}$. **Question 4** (a) 2.0×10^{12}; (b) 1.4×10^{13}; (c) 80 minutes. **Question 5** (a) 16, 8, 4, 2; (b) each coin lands randomly, so any single run varies about the average; (c) for example, use more coins or combine all groups' results — a larger sample varies less about the average. **Question 6** (a) 400, 200, 100, 50; (b) smooth curve falling steeply at first then flattening; (c) 50 minutes. **Question 7** $25\,\mathrm{MBq}$. **Question 8** 120 years. **Question 9** 15 minutes. **Question 10** $1.0\,\mu\mathrm{g}$. **Question 11** $\frac{1}{32}$; 3.1%. **Question 12** $1:8$. **Question 13** Which nucleus decays next, and when, cannot be predicted; with an enormous number of nuclei the same fraction decays in each equal interval, so the average behaviour of the sample is predictable. **Question 14** In the second half-life only half of the *remaining* nuclei decay, not half of the original sample; $\frac{1}{4}$ remains. **Question 15** The half-lives are identical — the half-life is a property of the isotope, not the sample size. **Question 16** The activity stays high enough through the scan but falls away within roughly a day, limiting the patient's exposure; a 6.0-year isotope would barely decay during the scan and would remain active in the patient for years. **Question 17** The sample contains a finite number of nuclei; the halving rule describes the average behaviour, and when only a few nuclei remain the random nature of decay dominates and the last nuclei decay one by one. **Question 18** Well: each coin "decays" randomly with a fixed chance per throw, and the number remaining halves on average each throw. Limitations: a small number of coins gives bumpy results compared with a real sample's enormous number of nuclei; the chance of decay is fixed at one in two rather than set by the isotope (also, time advances in jumps of one throw).

Fully-worked solutions

Question 1 $t_{1/2}=3.8$ days, initial activity $1200\,\mathrm{Bq}$. (a) The half-life of a radioisotope is the time taken for half of the undecayed nuclei in a sample to decay — equivalently, the time for the activity (or count rate) to fall to half its starting value. (b) After one half-life the activity halves: $1200\div2=600\,\mathrm{Bq}$. (c) $11.4\div3.8=3$ half-lives. $A=1200\times\left(\frac{1}{2}\right)^3=1200\times\frac{1}{8}=150\,\mathrm{Bq}$. (d) Fraction decayed $=1-\left(\frac{1}{2}\right)^3=1-\frac{1}{8}=\frac{7}{8}$.

Question 2 Each reading is exactly half the previous one, and the readings are 5.0 minutes apart. (a) The count rate halves every 5.0 minutes, so $t_{1/2}=5.0$ minutes. (b) 25 minutes is one further half-life after 20 minutes: $30\div2=15\,\text{counts min}^{-1}$. (c) $7.5\,\text{counts min}^{-1}$ is half of $15\,\text{counts min}^{-1}$, so it occurs one more half-life later: $25+5.0=30$ minutes.

Question 3 $t_{1/2}=6.0$ hours, initial activity $900\,\mathrm{MBq}$. (a) $n=\frac{24}{6.0}=4$ half-lives. (b) Fraction remaining $=\left(\frac{1}{2}\right)^4=\frac{1}{16}$. (c) $A=900\times\frac{1}{16}=56.25\,\mathrm{MBq}=56\,\mathrm{MBq}$ to two significant figures.

Question 4 $N_0=1.6\times10^{13}$, $t_{1/2}=20$ minutes. (a) $n=\frac{60}{20}=3$ half-lives, so $N=1.6\times10^{13}\times\left(\frac{1}{2}\right)^3=1.6\times10^{13}\times\frac{1}{8}=2.0\times10^{12}$. (b) Number decayed $=N_0-N=1.6\times10^{13}-2.0\times10^{12}=1.4\times10^{13}$. (c) $\frac{1.0\times10^{12}}{1.6\times10^{13}}=\frac{1}{16}=\left(\frac{1}{2}\right)^4$, so 4 half-lives have elapsed: $t=4\times20=80$ minutes.

Question 5 (a) About half of the remaining coins are removed on each throw, so the expected numbers are:

Throw	0 (start)	1	2	3	4
Expected number remaining	32	16	8	4	2

(b) Each coin lands randomly, so the number removed on any throw only *averages* half. With just 32 coins, a single run varies noticeably about the expected values — in the same way that real measurements on small samples vary about the predicted decay curve.

(c) Use many more coins, or combine every group's results into one large data set. The larger the sample, the closer the fraction removed on each throw sits to one half, so the results move closer to the expected values — this is exactly why real samples, with their enormous number of nuclei, decay so smoothly.

Question 6 (a) The activity halves every 10 minutes:

Time (min)	0	10	20	30	40
Activity (Bq)	800	400	200	100	50

(b) Plot the five points and join them with a smooth curve: it falls steeply at first and then flattens, dropping by half every 10 minutes.

(c) $25\,\text{Bq}$ is half of $50\,\text{Bq}$, so it occurs one further half-life after 40 minutes: $40+10=50$ minutes. (Reading from your curve, values of about 49–51 minutes are acceptable.)

Question 7 $n=\frac{32}{8.0}=4$ half-lives.

$$A=400\times\left(\frac{1}{2}\right)^4=400\times\frac{1}{16}=25\,\text{MBq}.$$

Question 8 $\frac{1}{16}=\left(\frac{1}{2}\right)^4$, so 4 half-lives must elapse:

$$t=4\times 30=120\,\text{years}.$$

Question 9 The count rate falls by a factor of $\frac{360}{45}=8=2^3$, so three half-lives have elapsed in 45 minutes:

$$t_{1/2}=\frac{45}{3}=15\,\text{minutes}.$$

Question 10 $n=\frac{45}{15}=3$ half-lives. The same halving model applies to the mass of undecayed isotope:

$$m=8.0\times\left(\frac{1}{2}\right)^3=8.0\times\frac{1}{8}=1.0\,\mu\text{g}.$$

Question 11 Fraction remaining after five half-lives:

$$\left(\frac{1}{2}\right)^5=\frac{1}{32}\approx 0.031=3.1\,\%.$$

Question 12 In 8.0 days, isotope X completes $\frac{8.0}{2.0}=4$ half-lives, leaving $\left(\frac{1}{2}\right)^4=\frac{1}{16}$ of its starting activity, while isotope Y completes $\frac{8.0}{8.0}=1$ half-life, leaving $\frac{1}{2}$. Since the starting activities were equal,

$$\text{ratio}=\frac{1}{16}:\frac{1}{2}=1:8.$$

Question 13 For a single nucleus, "random" means there is no way to predict whether it will decay in the next second, or the next year — and nothing that can be done to the nucleus changes its chances. Each undecayed nucleus of a given isotope simply has the same fixed chance of decaying in any given time interval. A sample, however, contains an enormous number of nuclei, and when very many random events each have the same chance of occurring, the same *fraction* of them occurs in every equal time interval. The average behaviour is therefore highly predictable even though each individual decay is not: half of the undecayed nuclei will decay in each half-life, whatever the sample is doing.

Question 14 The error is in the second half-life. During the second half-life, half of the nuclei **still remaining** decay — not half of the original sample. After one half-life $\frac{1}{2}$ of the original sample remains; the second half-life removes half of that $\frac{1}{2}$, leaving

$$\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$$

of the original sample. After two half-lives, $\frac{1}{4}$ remains undecayed (and $\frac{3}{4}$ has decayed); the sample is far from gone, and $\frac{1}{8}$ still remains after three half-lives.

Question 15 The two samples have **the same half-life**. The half-life is a property of the isotope — it is set by the fixed chance that any one nucleus of that isotope decays in a given time interval — and does not depend on how many nuclei are present. The larger sample starts with a higher activity (twice as many nuclei means twice as many decays per second on average), but it also has twice as much to lose, so the *fraction* decaying in each interval, and hence the time to halve, is identical for both samples.

Question 16 For a scan lasting several hours, the isotope's activity must stay high enough to produce a useful signal throughout the scan, then fade quickly afterwards so the patient is not exposed to radiation for longer than necessary. With a 6.0-hour half-life, technetium-99m loses only a fraction of its activity during a several-hour scan, yet within about a day (four half-lives) only $\frac{1}{16}$ remains. An isotope with a 6.0-year half-life would barely decay at all during the scan and would remain active in the patient's body for many years, delivering a far larger total dose. The 6.0-hour isotope is therefore matched to the task; the 6.0-year isotope is not.

Question 17 The halving rule is a statement about *average* behaviour: with a very large number of nuclei, very nearly half decay in each half-life. But a real sample contains a finite number of nuclei. As the sample decays, the number remaining becomes smaller and smaller, and with only a handful of nuclei left the random nature of decay dominates — you can no longer have "half of three nuclei". The last few nuclei decay one at a time, at unpredictable moments, and eventually the final undecayed nucleus decays. The model's never-reaching-zero curve describes the large-number behaviour of the sample; the real sample's finite number of nuclei guarantees that it does, eventually, reach zero.

Question 18 Ways the coin model represents real decay well: (1) each coin "decays" randomly — no throw's outcome can be predicted for any individual coin, just as no individual nucleus's decay can be predicted; (2) every coin has the same fixed chance (one in two) of decaying on each throw, producing the same constant-fraction decay as a real isotope — the number remaining halves, on average, every throw, giving the model a definite half-life. Limitations: (1) 32 coins is a tiny sample — real samples contain enormous numbers of nuclei — so the results are far bumpier than a real decay curve, which is smooth; (2) the chance of decay is fixed by the coin at one in two, whereas each real isotope has its own decay chance and hence its own half-life (further, time advances in jumps of one throw rather than continuously). Improving the model would require many more coins, or many repeated runs combined, to smooth out the variation.

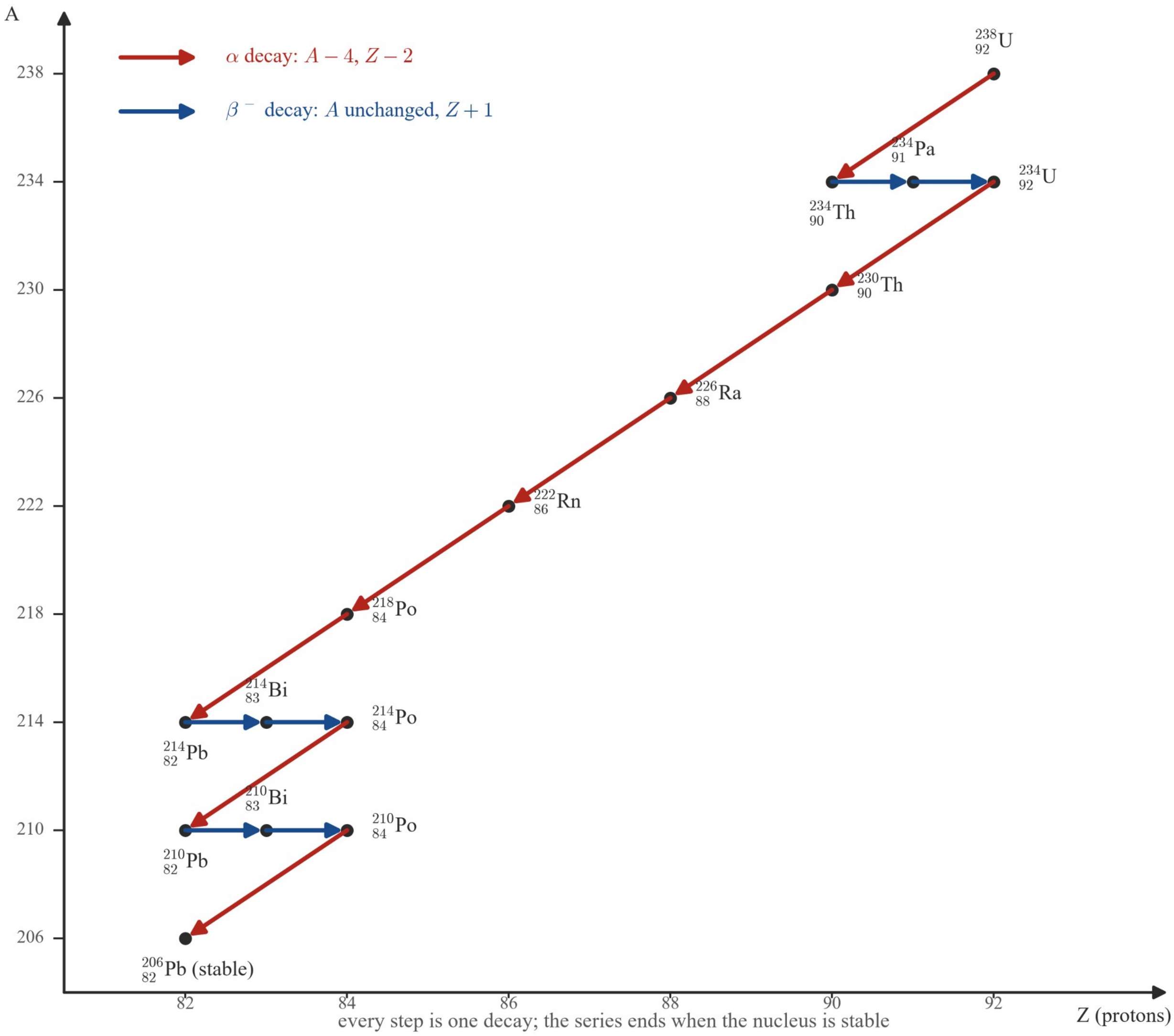
Theory

From one decay to a chain of decays. A single radioactive decay does not always produce a stable nucleus. Very often, the nucleus produced by a decay is itself unstable and decays again, and the process repeats. A **decay series** is the sequence of decays that starts from an unstable **parent isotope** and passes through a chain of **daughter isotopes** until a **stable isotope** is reached — an isotope whose nucleus does not decay at all. Whether a particular nucleus is stable or unstable is determined by the forces inside the nucleus, as explained in Section 3A. Each step of a series is one of the four types of decay covered in Section 3B: α, β^-, β^+ or γ.

Reading a decay series diagram. A **decay series diagram** sets a whole series out on one graph. Each isotope in the series is drawn as a labelled point, and each decay is drawn as an arrow from one isotope to the next. The axes are:

- the **proton number** Z (the number of protons in the nucleus) on the horizontal axis;
- the **nucleon number** A (the total number of protons and neutrons in the nucleus) on the vertical axis.

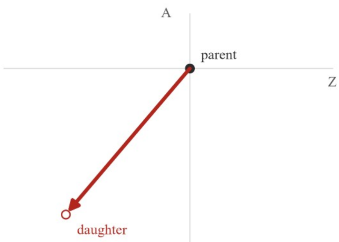
Because each type of decay changes A and Z by fixed amounts, the type of each decay can be read directly from the direction and length of its arrow. Reading a diagram this way is what it means to analyse a decay series diagram.



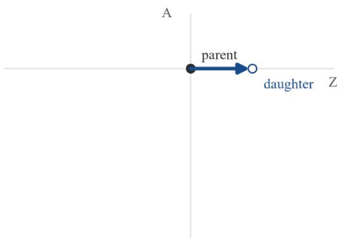
How each decay moves an isotope on the diagram. Section 3B showed how the four emissions change a nucleus. On a decay series diagram those changes become movements:

Decay	What leaves the nucleus	Change in A	Change in Z	Movement on the diagram
α	a helium-4 nucleus (2 protons + 2 neutrons)	−4	−2	diagonal step down and left
β^-	an electron	0	+1	one step to the right
β^+	a positron	0	−1	one step to the left
γ	a γ ray (energy only)	0	0	no movement

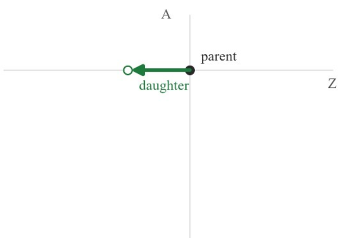
An α step is easy to pick out: it is the only decay that changes A, so it is the only diagonal arrow on the diagram. A β^- step leaves A unchanged and increases Z by 1, so it is a short horizontal arrow pointing to the right; a β^+ step is a short horizontal arrow pointing to the left. A γ ray carries energy only, so it changes neither A nor Z and produces no movement at all. γ emission often happens immediately after an α or β^- decay, when the daughter nucleus is left with excess energy that it must release.



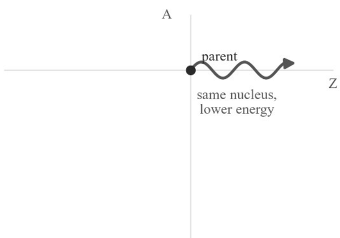
α: a helium nucleus leaves — $A-4$, $Z-2$



β^-: neutron → proton — $Z+1$, A unchanged



β^+: proton → neutron — $Z-1$, A unchanged



γ: excess energy leaves — A and Z unchanged

The proton number fixes which element a nucleus is, so α, β^- and β^+ decays all transform one element into another, while γ emission does not. A series also passes through the same element more than once, at different nucleon numbers: the uranium-238 series, for example, contains both uranium-238 and uranium-234. These are **isotopes** of uranium — nuclei with the same proton number but different nucleon numbers. The elements used in this subtopic are:

Element	Symbol	Z	Element	Symbol	Z
iron	Fe	26	radon	Rn	86
cobalt	Co	27	radium	Ra	88
nickel	Ni	28	actinium	Ac	89
thallium	Tl	81	thorium	Th	90
lead	Pb	82	protactinium	Pa	91
bismuth	Bi	83	uranium	U	92
polonium	Po	84	neptunium	Np	93

Counting the decays in a series. The net change between the parent and the stable end product fixes how many decays of each type occurred. Only α decay changes A, and each α decay lowers it by exactly 4, so the number of α decays is

$$n_\alpha = \frac{A_{\text{start}} - A_{\text{end}}}{4}.$$

Then consider Z. Each α decay removes 2 protons and each β^- decay turns a neutron into a proton and so adds 1, giving

$$Z_{\text{end}} = Z_{\text{start}} - 2n_\alpha + n_{\beta^-}, \text{so } n_{\beta^-} = Z_{\text{end}} - Z_{\text{start}} + 2n_\alpha.$$

γ emissions never enter the count because they change neither A nor Z. The order of the decays does not matter either: only the total change matters.

The uranium-238 series. The best-known series begins with uranium-238 ($A = 238$, $Z = 92$) and ends with stable lead-206. Its fourteen steps are:

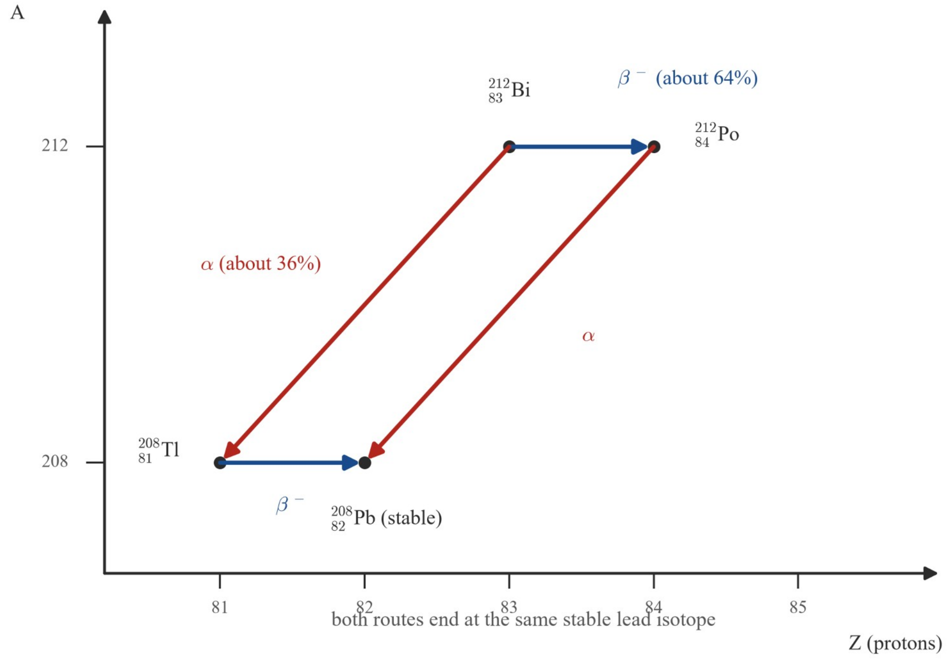
Step	Decay	Isotope produced	A	Z
1	α	thorium-234	234	90
2	β^-	protactinium-234	234	91
3	β^-	uranium-234	234	92
4	α	thorium-230	230	90
5	α	radium-226	226	88
6	α	radon-222	222	86
7	α	polonium-218	218	84
8	α	lead-214	214	82
9	β^-	bismuth-214	214	83
10	β^-	polonium-214	214	84
11	α	lead-210	210	82
12	β^-	bismuth-210	210	83
13	β^-	polonium-210	210	84
14	α	lead-206 (stable)	206	82

The three natural series. Three decay series occur naturally on Earth, because their parent isotopes have very long half-lives — uranium-238 about 4.5 billion years, comparable with the age of the Earth, and thorium-232 about 14 billion years — and so have not all decayed away. Each step of a series has its own half-life, and Section 3C shows how half-lives are used to model the rate of decay. All three natural series end at stable isotopes of lead:

Series starts at	Series ends at	α decays	β^- decays
uranium-238	lead-206	8	6
uranium-235	lead-207	7	4
thorium-232	lead-208	6	4

The series stop at lead because nuclei with more than 82 protons have no stable isotopes: as Z grows, the electrostatic repulsion between the protons becomes harder for the short-range strong nuclear force to balance (Section 3A). Lead, $Z = 82$, is the heaviest element with stable isotopes, and lead-208 is the heaviest stable isotope known. A series cannot stop before it reaches stability — every intermediate isotope is unstable and must decay again.

Branching. At most steps of a series only one type of decay is possible, but a few isotopes can decay in two different ways. In the thorium series, bismuth-212 can emit either an α particle or a β^- particle. On a decay series diagram the series then splits into two paths at that isotope. As Example 4 shows, the two paths still arrive at the same stable end product.



Where the series are found. The uranium-238 series is present in uranium ores such as those mined at Olympic Dam in South Australia and at the Ranger mine in the Northern Territory. The thorium-232 series is found in monazite, a mineral that contains thorium and occurs in Australian mineral-sand deposits such as those of the Murray Basin in Victoria. One member of the uranium-238 series, radon-222, is a gas, and it can seep out of the ground and into buildings constructed over granite. β^+ decays occur in series of artificially produced isotopes and in space: the light of SN 1987A — the explosion of a massive star, called a supernova, observed from Australia in February 1987 — was powered by a short chain of decays ending at stable iron-56. Writing the decay equations themselves is the work of Section 3B; this subtopic is about reading the series as a whole, and the effects the radiation has on humans are taken up in Section 3E.

Worked examples

Example 1 — scaffolded

The ore mined at Olympic Dam in South Australia contains uranium-238, the parent isotope of one of the natural decay series. The first four steps of the uranium-238 series are uranium-238 → thorium-234 → protactinium-234 → uranium-234 → thorium-230. Identify the type of decay (α, β^-, β^+ or γ) at each of the four steps.

Working	Comment
Step 1: uranium-238 → thorium-234. $\Delta A = 234 - 238 = -4$; $\Delta Z = 90 - 92 = -2$.	A falls by 4 and Z falls by 2, which matches α decay.
Step 2: thorium-234 → protactinium-234. $\Delta A = 0$; $\Delta Z = 91 - 90 = +1$.	A unchanged and Z up by 1 matches β^- decay — a neutron has changed into a proton.
Step 3: protactinium-234 → uranium-234. $\Delta A = 0$; $\Delta Z = 92 - 91 = +1$.	The same changes again: a second β^- decay.
Step 4: uranium-234 → thorium-230. $\Delta A = 230 - 234 = -4$; $\Delta Z = 90 - 92 = -2$.	The changes match α decay again.

∴ the four steps are α, β^-, β^- and α in that order. Every step of a series can be identified from its change in A and Z alone.

Example 2 — scaffolded

A sample of uranium ore from the Ranger mine in the Northern Territory contains uranium-238 nuclei at every stage of the series. Determine how many α decays and how many β⁻ decays occur in the complete series from uranium-238 ($A=238$, $Z=92$) to stable lead-206 ($A=206$, $Z=82$).

Working	Comment
$\Delta A=238-206=32$.	Compare the nucleon numbers of the parent and the end product.
$n_\alpha=\frac{32}{4}=8$.	Only α decay changes A, and each α decay lowers it by 4.
Z after the α decays alone: $92-2\times 8=76$.	Each α decay removes 2 protons.
The series actually ends at $Z=82$, so β⁻ decays must add $82-76=6$ protons: $n_{\beta^-}=6$.	Each β⁻ decay turns a neutron into a proton, raising Z by 1.

∴ the uranium-238 series contains 8 α decays and 6 β⁻ decays. This agrees with the series table above, which lists 8 α steps and 6 β⁻ steps. ✓

Example 3 — unscaffolded

Monazite, a mineral found in Australian mineral-sand deposits such as those of the Murray Basin in Victoria, contains thorium-232, the parent isotope of the thorium decay series. The series ends at stable lead-208. Determine the number of α decays and the number of β⁻ decays in the thorium series, and identify the daughter isotope produced by the very first decay of thorium-232 ($A=232$, $Z=90$).

The nucleon number falls from 232 to 208, a change of 24. Only α decay changes A, and each α decay lowers it by 4, so the number of α decays is

$$n_\alpha=\frac{232-208}{4}=\frac{24}{4}=6.$$

The proton number starts at 90. The six α decays remove $2\times 6=12$ protons, and the β⁻ decays add one proton each. Since the series ends at lead, $Z=82$,

$$82=90-12+n_{\beta^-},\text{so}\, n_{\beta^-}=4.$$

The first decay of thorium-232 is an α decay, so the daughter has $A=232-4=228$ and $Z=90-2=88$. The element with $Z=88$ is radium.

∴ the thorium series contains 6 α decays and 4 β⁻ decays, and the first daughter isotope is radium-228.

Example 4 — unscaffolded

At most steps of a decay series only one type of decay is possible, but bismuth-212 ($A=212$, $Z=83$) in the thorium series can decay in two ways: about 64% of bismuth-212 nuclei decay by β⁻ emission and about 36% by α emission. Show that the two decay paths of bismuth-212 both end at the same stable isotope, lead-208.

Path 1 — β⁻ decay first. The β⁻ decay leaves A unchanged and raises Z by 1, taking bismuth-212 to polonium-212 ($A=212$, $Z=84$). Polonium-212 then decays by α emission: A falls by 4 and Z falls by 2, giving $A=208$ and $Z=82$ — lead-208.

Path 2 — α decay first. The α decay takes bismuth-212 to the isotope with $A=208$ and $Z=81$, which is thallium-208. Thallium-208 then decays by β⁻ emission, leaving A unchanged and raising Z to 82 — again lead-208.

Both paths involve one α decay and one β⁻ decay, just in a different order, so the net change is the same either way: $\Delta A=-4$ and $\Delta Z=-1$. That is why a decay series diagram can split into two branches at bismuth-212 and still finish at the single stable isotope lead-208. (Some of these steps are also accompanied by γ emission, which releases excess energy and moves the isotope nowhere on the diagram.)

∴ both decay paths of bismuth-212 end at stable lead-208.

Practice questions

Question 1 The table below summarises how each type of decay changes a nucleus and how that decay appears on a decay series diagram.

Decay	Change in A	Change in Z	Movement on the diagram
α			
β^-			
β^+			
γ			

(a) Copy and complete the table.
(b) State which of the four decays change the identity of the element, and explain your answer.
(c) A nucleus undergoes one of the four decays and its position on the diagram does not change. State the decay, and say what the nucleus has lost.

Question 2 Radon-222 is formed partway through the uranium-238 series. The table lists the isotopes the series passes through after radon-222 forms, in order.

Isotope	A	Z
radon-222	222	86
polonium-218	218	84
lead-214	214	82
bismuth-214	214	83
polonium-214	214	84
lead-210	210	82

(a) For each consecutive pair of isotopes, calculate the change in A and the change in Z.
(b) Classify each of the five decays as α, β^-, β^+ or γ.
(c) Identify, with a reason, two pairs of isotopes in the table that are isotopes of the same element.

Question 3 Natural uranium is mostly uranium-238, but about 0.7% is uranium-235, the isotope that undergoes fission in nuclear reactors (Chapter 4). The uranium-235 series ends at stable lead-207. Uranium has $Z = 92$ and lead has $Z = 82$. (a) Show, using the nucleon numbers only, that the uranium-235 series contains exactly 7 α decays. (b) Calculate the number of β^- decays in the uranium-235 series. (c) Explain why nothing needs to be known about γ emission to answer parts (a) and (b).

Question 4 Thorium-228 ($Z = 90$) is a member of the thorium decay series. Its first four decays are all α decays. (a) Identify, giving its A and Z, the daughter isotope produced by the first α decay of thorium-228. (b) Identify the isotope present after all four α decays have occurred. (c) This isotope then decays by β^- emission. Identify the product isotope and state what has changed inside the nucleus.

Question 5 In February 1987 a massive star exploded in the Large Magellanic Cloud, a small companion galaxy of the Milky Way. The supernova, SN 1987A, was visible with the naked eye from Australia, and its glow was powered by the decay of freshly made radioactive isotopes. One of them, cobalt-56 ($Z = 27$), decays by β^+ emission to a stable isotope. (a) State the change in A and the change in Z in a β^+ decay. (b) Identify the isotope produced by the β^+ decay of cobalt-56. (c) Describe how this decay would appear on a decay series diagram.

Question 6 Three decay series occur naturally on Earth. (a) Define a stable isotope. (b) Copy and complete the table, naming the stable isotope at which each natural series ends.

Parent isotope	Stable end isotope
uranium-238	
uranium-235	
thorium-232	

(c) All three series end at isotopes of the same element. Explain why the natural series stop where they do, referring to the forces in the nucleus (Section 3A).

Question 7 Marie and Pierre Curie discovered radium in uranium ore in 1898. The isotope they isolated, radium-226 ($Z=88$), is a member of the uranium-238 series and decays through a sequence of α and β^- decays to stable lead-206 ($Z=82$). Calculate the number of α decays and the number of β^- decays between radium-226 and lead-206.

Question 8 Radon-222 ($A=222$, $Z=86$) that has seeped into the air of a building continues to decay. Its next four decays are α, α, β^- and β^- in that order. Identify, giving the name, A and Z, the isotope formed after each of the four decays.

Question 9 Isotopes that do not occur naturally can be produced in nuclear reactors. One of them, neptunium-237 ($Z=93$), is the parent isotope of a decay series that ends at bismuth-209 ($Z=83$), an isotope so long-lived that it is effectively stable. Calculate the number of α decays and the number of β^- decays in this series.

Question 10 Lead-210 ($Z=82$), a member of the uranium-238 series, settles into the sediments of lakes and oceans and is used to date them. From lead-210, the series continues with β^-, β^- and α decays, and then stops. Identify the isotope formed at each of the three steps, and explain why the series stops there.

Question 11 The decay chain that powered the glow of SN 1987A began with nickel-56 ($Z=28$), which transformed into cobalt-56; the cobalt-56 then decayed by β^+ emission to stable iron-56. (a) Identify the isotope formed by the β^+ decay of cobalt-56 ($Z=27$). (b) State the total change in A and the total change in Z between nickel-56 and the stable end product. (c) State, with a reason, whether the proton number rose or fell when nickel-56 transformed into cobalt-56, and by how much.

Question 12 Each of the following decays is a single step of the uranium-238 series. In each case identify the parent isotope, giving its name, A and Z. (a) An isotope decays by α emission to lead-210 ($Z=82$). (b) An isotope decays by β^- emission to bismuth-214 ($Z=83$). (c) An isotope decays by α emission to radon-222 ($Z=86$).

Question 13 γ emission often follows immediately after an α or β^- decay. Explain why a γ emission produces no movement on a decay series diagram, and why it so often accompanies the other two decays.

Question 14 Explain why every decay series eventually comes to an end, and explain why none of the three natural series can end at an isotope of uranium or thorium.

Question 15 A student studying the uranium-238 series says: “Uranium-238 and uranium-234 are both uranium, so they are the same isotope.” Evaluate this claim.

Question 16 A decay series diagram is printed with no labels on its arrows. Explain how the direction and length of the arrows alone allow you to decide which steps are α decays and which are β^- decays.

Question 17 Granite contains traces of uranium-238, and buildings constructed on some granites can have radon-222 gas seeping up from the ground into them. Radon-222 is a member of the uranium-238 series and is a chemically unreactive gas. (a) The Earth is about 4.5 billion years old. Explain why uranium-238 decay series are still active in granite today. (b) Explain why radon-222, rather than the other members of the series, is the isotope that moves out of the rock and into buildings.

Question 18 Bismuth-212 ($Z=83$) is a member of the thorium series and can decay by either α emission or β^- emission. Explain how the two decay paths can start from the same isotope and still arrive at the same stable end product, lead-208. Your answer should refer to the changes in A and Z along each path.

Answers

Question 1 (a) α: −4, −2, diagonal step down and left; β^-: 0, +1, one step to the right; β^+: 0, −1, one step to the left; γ: 0, 0, no movement; (b) α, β^- and β^+ — they change Z, and Z fixes the element; (c) γ emission; the nucleus has lost energy only. **Question 2** (a) −4/−2, −4/−2, 0/+1, 0/+1, −4/−2; (b) α, α, β^-, β^-, α; (c) polonium-218 and polonium-214 ($Z=84$); lead-214 and lead-210 ($Z=82$). **Question 3** (a) $\Delta A=235-207=28$; $28\div4=7$ α decays; (b) 4 β^- decays; (c) γ emission changes neither A nor Z. **Question 4** (a) radium-224 ($A=224$, $Z=88$); (b) lead-212 ($A=212$, $Z=82$); (c) bismuth-212 ($A=212$, $Z=83$); a neutron has changed into a proton. **Question 5** (a) $\Delta A=0$, $\Delta Z=-1$; (b) iron-56 ($A=56$, $Z=26$); (c) one step to the left, at the same height (same A). **Question 6** (a) an isotope whose nucleus does not decay; (b) lead-206; lead-207; lead-208; (c) see solution. **Question 7** 5 α decays and 4 β^- decays. **Question 8** polonium-218 (218, 84); lead-214 (214, 82); bismuth-214 (214, 83); polonium-214 (214, 84). **Question 9** 7 α decays and 4 β^- decays. **Question 10** bismuth-210; polonium-210; lead-206; the series stops because lead-206 is stable. **Question 11** (a) iron-56 ($Z=26$); (b) $\Delta A=0$, $\Delta Z=-2$; (c) fell by 1 — cobalt has one fewer proton than nickel. **Question 12** (a) polonium-214 ($A=214$, $Z=84$); (b) lead-214 ($A=214$, $Z=82$); (c) radium-226 ($A=226$, $Z=88$). **Question 13** See solution (a γ ray changes neither A nor Z; the daughter nucleus is releasing excess energy). **Question 14** See solution (series end at stability; every isotope of uranium and thorium is unstable). **Question 15** The claim is false; they are two different isotopes of the same element (146 neutrons against 142). **Question 16** See solution (α steps are diagonal down-left steps; β^- steps are short horizontal steps to the right). **Question 17** See solution (the half-life of uranium-238 is comparable with the age of the Earth; radon is the only member of the series that is a gas). **Question 18** See solution (both paths have the same net change: $\Delta A=-4$, $\Delta Z=-1$).

Fully-worked solutions

Question 1 (a) The completed table is:

Decay	Change in A	Change in Z	Movement on the diagram
α	−4	−2	diagonal step down and left
β^-	0	+1	one step to the right
β^+	0	−1	one step to the left
γ	0	0	no movement

(b) α, β^- and β^+ decays change the identity of the element. The proton number Z fixes which element a nucleus is, and these three decays all change Z; γ emission leaves Z unchanged.

(c) The decay is γ emission. A γ ray carries energy only — no protons or neutrons leave the nucleus — so the nucleus has lost energy and nothing else.

Question 2 (a) Taking each consecutive pair:

Decay	ΔA	ΔZ
radon-222 → polonium-218	−4	−2
polonium-218 → lead-214	−4	−2
lead-214 → bismuth-214	0	+1
bismuth-214 → polonium-214	0	+1
polonium-214 → lead-210	−4	−2

(b) $\Delta A=-4$ with $\Delta Z=-2$ is α decay; $\Delta A=0$ with $\Delta Z=+1$ is β^- decay. The five decays are therefore α, α, β^-, β^-, α.

(c) Isotopes are nuclei with the same proton number but different nucleon numbers. Polonium-218 and polonium-214 both have $Z=84$ (different A), and lead-214 and lead-210 both have $Z=82$ (different A), so each pair is a pair of isotopes of one element.

Question 3 Uranium-235 has $A=235$; lead-207 has $A=207$. (a) The nucleon number falls by $235-207=28$. Only α decay changes A, and each α decay lowers it by 4, so the number of α decays is $28\div4=7$. (b) The seven α decays lower Z by $2\times7=14$, from 92 to 78. The series actually ends at $Z=82$, so β⁻ decays must add $82-78=4$ protons: there are 4 β⁻ decays. (c) γ emission changes neither A nor Z, so γ emissions cannot affect either count.

∴ the uranium-235 series contains 7 α decays and 4 β⁻ decays.

Question 4 Thorium-228 has $A=228$, $Z=90$. (a) One α decay lowers A by 4 and Z by 2: $A=224$, $Z=88$. The element with $Z=88$ is radium, so the daughter is radium-224. (b) Four α decays lower A by $4\times4=16$ and Z by $4\times2=8$: $A=228-16=212$ and $Z=90-8=82$. The element with $Z=82$ is lead, so the isotope is lead-212. (c) A β⁻ decay leaves A unchanged and raises Z by 1: $A=212$, $Z=83$, which is bismuth-212. Inside the nucleus, one neutron has changed into a proton (the β⁻ particle is the electron released by that change).

Question 5 (a) In a β⁺ decay, $\Delta A=0$ and $\Delta Z=-1$: a proton changes into a neutron and a positron is emitted. (b) Cobalt-56 has $A=56$, $Z=27$. After β⁺ decay, $A=56$ and $Z=26$. The element with $Z=26$ is iron, so the product is iron-56, which is stable. (c) On a decay series diagram the arrow is one step to the left (proton number down by 1) at the same height (nucleon number unchanged): a short horizontal arrow pointing left.

Question 6 (a) A stable isotope is an isotope whose nucleus does not decay: it undergoes no further radioactive transformation. (b) The three natural series end at:

Parent isotope	Stable end isotope
uranium-238	lead-206
uranium-235	lead-207
thorium-232	lead-208

(c) Nuclei with more than 82 protons have no stable isotopes: as Z grows, the electrostatic repulsion between the protons becomes too large for the short-range strong nuclear force to balance (Section 3A). Lead, $Z=82$, is the heaviest element with stable isotopes, so each natural series continues until it reaches a stable lead isotope and can go no further.

Question 7 Radium-226 has $A=226$, $Z=88$; lead-206 has $A=206$, $Z=82$. The nucleon number falls by $226-206=20$, and only α decay changes A, by 4 each time, so the number of α decays is $20\div4=5$. The five α decays lower Z by $2\times5=10$, from 88 to 78. The series ends at $Z=82$, so β⁻ decays must add $82-78=4$ protons: there are 4 β⁻ decays.

∴ there are 5 α decays and 4 β⁻ decays between radium-226 and lead-206.

Question 8 Starting from radon-222 ($A=222$, $Z=86$):

Decay	Change	Isotope formed
α	A: $222-4=218$; Z: $86-2=84$	polonium-218
α	A: $218-4=214$; Z: $84-2=82$	lead-214
β⁻	A: 214 unchanged; Z: $82+1=83$	bismuth-214
β⁻	A: 214 unchanged; Z: $83+1=84$	polonium-214

∴ the isotopes formed are polonium-218, lead-214, bismuth-214 and polonium-214.

Question 9 Neptunium-237 has $A=237$, $Z=93$; bismuth-209 has $A=209$, $Z=83$. The nucleon number falls by $237-209=28$, and each α decay lowers A by 4, so the number of α decays is $28\div4=7$. The seven α decays lower Z by $2\times7=14$, from 93 to 79. The series ends at $Z=83$, so β⁻ decays must add $83-79=4$ protons.

∴ the series contains 7 α decays and 4 β⁻ decays.

Question 10 Starting from lead-210 ($A=210$, $Z=82$):

Decay	Change	Isotope formed
β^-	A: 210 unchanged; Z: $82+1=83$	bismuth-210
β^-	A: 210 unchanged; Z: $83+1=84$	polonium-210
α	A: $210-4=206$; Z: $84-2=82$	lead-206

The series stops at lead-206 because lead-206 is a stable isotope: its nucleus does not decay, so there is no next step.

Question 11 (a) Cobalt-56 has $A=56$, $Z=27$. A β^+ decay leaves A unchanged and lowers Z by 1, giving $A=56$, $Z=26$ — iron-56, which is stable. (b) Nickel-56 has $A=56$, $Z=28$; the end product iron-56 has $A=56$, $Z=26$. The total change is $\Delta A=0$ and $\Delta Z=-2$. (c) The proton number fell, by 1: nickel has $Z=28$ and cobalt has $Z=27$, so the nickel-56 → cobalt-56 transformation removed one proton from the nucleus.

Question 12 Work backwards from the product, undoing the decay's change in A and Z. (a) α emission took A down by 4 and Z down by 2, so the parent had $A=210+4=214$ and $Z=82+2=84$. $Z=84$ is polonium: the parent was polonium-214. (b) β^- emission left A unchanged and raised Z by 1, so the parent had $A=214$ and $Z=83-1=82$. $Z=82$ is lead: the parent was lead-214. (c) α emission took A down by 4 and Z down by 2, so the parent had $A=222+4=226$ and $Z=86+2=88$. $Z=88$ is radium: the parent was radium-226.

Question 13 Model answer points:

- A γ ray is electromagnetic radiation — energy only. No proton or neutron leaves the nucleus, so both A and Z are unchanged, and the isotope stays at the same point on the diagram: no movement.
- After an α or β^- decay, the daughter nucleus is often left with excess energy.
- The daughter releases that excess energy as a γ ray, which is why γ emission so often follows immediately after the other two decays rather than occurring on its own.

Question 14 Model answer points:

- A decay series ends when it reaches a stable isotope: a stable nucleus does not decay, so there are no further steps. Stability is set by the forces in the nucleus (Section 3A).
- Every isotope of uranium ($Z=92$) and thorium ($Z=90$) is unstable, because nuclei with more than 82 protons have no stable isotopes — the electrostatic repulsion between so many protons cannot be balanced by the short-range strong nuclear force.
- A series that reached an isotope of uranium or thorium would therefore be forced to keep decaying; each natural series continues until it reaches a stable isotope of lead, the heaviest element with stable isotopes.

Question 15 Model answer points:

- The claim is **false**.
- Isotopes are nuclei of the same element (same proton number Z) with different nucleon numbers A. Uranium-238 and uranium-234 both have $Z=92$, so they are the same *element*, uranium.
- But they have different nucleon numbers — 238 and 234 — and hence different numbers of neutrons: $238-92=146$ against $234-92=142$.
- They are therefore two *different isotopes* of uranium, not the same isotope. This is exactly why both can appear on the one decay series diagram: same Z, different A.

Question 16 Model answer points:

- An α decay lowers A by 4 and Z by 2, so an α step is the only arrow that moves diagonally on the diagram — down and to the left — and it is a relatively long step (4 units of A).
- A β^- decay leaves A unchanged and raises Z by 1, so a β^- step is a short horizontal arrow pointing to the right.

- The two are therefore easy to tell apart: diagonal, down-left steps are α decays; short, horizontal, rightward steps are β⁻ decays. (A short horizontal step to the *left* would be β⁺, and a step with no movement at all would be γ.)

Question 17 Model answer points:

-
  (a) Uranium-238 has a half-life of about 4.5 billion years, comparable with the age of the Earth, so a large fraction of the uranium-238 originally present in the granite is still there and still decaying.
- Because the parent keeps decaying, every later member of the series, including radon-222, is continually being produced: the series is still active.
-
  (b) Every member of the series except radon is a solid locked inside the mineral grains of the rock. Radon-222 is a chemically unreactive gas, so once it forms it can move through tiny cracks and pores in the rock and soil and seep into buildings, where it can accumulate.

Question 18 Model answer points:

- Bismuth-212 has $A = 212$, $Z = 83$.
- **Path 1 (β⁻ first):** β⁻ decay takes it to polonium-212 ($A = 212$, $Z = 84$); a following α decay lowers A by 4 and Z by 2, giving $A = 208$, $Z = 82$ — lead-208.
- **Path 2 (α first):** α decay takes it to thallium-208 ($A = 208$, $Z = 81$); a following β⁻ decay raises Z by 1, giving $A = 208$, $Z = 82$ — again lead-208.
- Each path contains one α decay and one β⁻ decay, only in a different order, so the net change is identical either way: $\Delta A = -4$ and $\Delta Z = -1$.
- That is why the decay series diagram splits into two branches at bismuth-212 but both branches finish at the single stable isotope lead-208, where the series stops.

Chapter 3 Radiation from the nucleus — 3E The effect of radiation on humans, and radiation dose

Theory

Radioactive sources emit α, β and γ radiation that carries energy away from the decaying nucleus (Section 3B). When that radiation meets the matter of the human body, the energy is deposited in living tissue. Whether the result is harmless, harmful or useful depends on **how much** energy is deposited, **where** it is deposited, and **what kind** of radiation deposited it. This subtopic explains the biological effects of the three radiations and introduces the three quantities used to measure and calculate them: **absorbed dose**, **equivalent dose** and **effective dose**.

Ionising radiation removes electrons from atoms. The α, β and γ radiations from the nucleus are all forms of **ionising radiation**: radiation carrying enough energy to knock electrons out of the atoms it passes through. An atom that loses an electron is left as a charged particle called an **ion**, and the process is called **ionisation**. Because the chemistry of a cell depends on the electrons holding its molecules together, ionisation can break chemical bonds and change the molecules of the cell. This is the single mechanism behind every biological effect of these radiations — the three radiations differ only in how strongly and how deeply they ionise.

How ionising radiation damages cells. The most important target in a cell is its DNA, the molecule that carries the instructions for how the cell behaves and divides. When radiation ionises DNA, three things can happen:

- the cell **repairs** the damage and continues to function normally;
- the cell is **killed** and the body replaces it with a new one;
- the cell survives but is left with a **mutation** — altered instructions that can, in some cases, lead to cancer years later.

Cells that divide quickly (the cells of the bone marrow, the lining of the gut and the skin) are the most sensitive to radiation, because radiation does its worst damage to cells that are in the process of dividing. This is why those tissues and organs are the ones most at risk from a given dose.

Different capacities to cause cell damage. The three radiations cause different amounts of damage for the same deposited energy, because they ionise differently along their paths (Section 3B):

- **α radiation** consists of heavy, doubly charged particles that move relatively slowly. They ionise very densely — a great many ionisations packed into a very short track — and are stopped by a sheet of paper or by the dead outer layer of the skin. Where they do reach living cells, they do a great deal of damage.
- **β radiation** consists of fast, light particles — electrons (β^-) or positrons (β^+). They ionise less densely than α particles and travel further, penetrating several millimetres into tissue.
- **γ radiation** is electromagnetic radiation of very high frequency. It ionises sparsely but penetrates deeply, passing through the body and reaching the internal organs.

These different capacities to cause damage per unit of deposited energy are quantified by the **radiation weighting factor**, introduced below.

Sources outside and inside the body. The hazard a source presents depends on whether it is outside or inside the body, because the three radiations penetrate so differently. An **external source** irradiates the body from outside; an **internal source** enters the body — breathed in, swallowed, or taken in through a wound — and decays inside it, where there is no protective layer of dead skin between the source and the living cells.

Radiation	External source (outside the body)	Internal source (inside the body)
α	Least hazardous: stopped by the dead outer layer of skin, so it does not reach living cells (though it can harm the eyes or an open wound).	Most hazardous: all of its energy is deposited in a very short track inside living tissue, ionising densely.
β	Can burn the skin and damage the lens of the eye; a significant hazard	Hazardous: irradiates the cells surrounding the source.

Radiation	External source (outside the body)	Internal source (inside the body)
	at high intensities.	
γ	Most hazardous: penetrates through the skin and irradiates the internal organs.	Hazardous, although a large fraction of the γ radiation passes out of the body without interacting.

A real example of internal α exposure is the naturally occurring gas **radon**, which is emitted by rocks and soil and can collect in poorly ventilated buildings. When radon is breathed in, its solid decay products can lodge in the lungs and irradiate the sensitive lung tissue from the inside with α radiation.

Effects of low and high doses. The effects of radiation on the body fall into two broad groups, depending on the size of the dose and how quickly it is received.

High doses received over a short time kill large numbers of cells at once, and the tissue shows visible damage. These effects have a **threshold** — a dose below which the effect does not occur — and the severity of the effect increases with the dose. For a dose delivered to the whole body in a short time:

- about $1\,\text{Sv}$: the first symptoms of **acute radiation syndrome** (a group of serious symptoms including nausea, vomiting and fatigue) can appear within hours;
- about $1\text{–}2\,\text{Sv}$: acute radiation syndrome, with damage to the bone marrow and the blood;
- about $2\text{–}6\,\text{Sv}$: severe acute radiation syndrome, including hair loss and internal bleeding; without intensive medical treatment a dose of roughly $3\text{–}5\,\text{Sv}$ is fatal to about half of those exposed;
- about $10\,\text{Sv}$ or more: fatal within weeks.

Smaller doses to part of the body also have thresholds: about $2\,\text{Gy}$ to the skin causes temporary reddening, and high doses to the lens of the eye can cause cataracts.

Low doses — small doses, or doses spread out over a long time — do not kill enough cells to cause immediate illness. Instead, they leave a small number of mutated cells, and the effect is an increased **probability** of developing cancer years or decades later. There are no immediate symptoms, and the greater the dose the greater the probability (not the severity) of the effect. No dose below which this added risk is exactly zero has been demonstrated, so Australia's radiation protection limits are set on the cautious assumption that every dose, however small, carries some risk; the limits keep that added risk very small.

Radiation protection also takes account of long-term effects: cancers can take years to decades to appear after exposure, and effects on an unborn child are a particular concern for pregnant radiation workers. Genetic effects (mutations passed on to children) are observed in irradiated animals, but have not been clearly observed in the human populations studied to date.

Absorbed dose — energy deposited per kilogram. The most basic measure of how much radiation a body or tissue receives is the **absorbed dose** D: the energy E deposited by the radiation per kilogram of the material irradiated:

$$D = \frac{E}{m}$$

The unit of absorbed dose is the **gray** (Gy), named after the physicist Louis Harold Gray:

$$1\,\text{Gy} = 1\,\text{J kg}^{-1}.$$

An absorbed dose of $1\,\text{Gy}$ means that 1 joule of radiation energy has been deposited in each kilogram of the absorbing material. Absorbed dose says nothing about the *type* of radiation: $1\,\text{Gy}$ of α radiation and $1\,\text{Gy}$ of γ radiation deposit the same energy per kilogram, but, as the next quantity shows, they do not cause the same biological damage.

Equivalent dose — allowing for the type of radiation. To compare the biological damage from different radiations, the absorbed dose is multiplied by a **radiation weighting factor** w_R that represents how damaging each radiation is per gray. The result is the **equivalent dose** H:

$$H = w_R \times D$$

The unit of equivalent dose is the **sievert** (Sv), named after the Swedish physicist Rolf Sievert. The radiation weighting factors used in Australia are:

Radiation	Radiation weighting factor w_R
γ	1
β	1
α	20

Source: ICRP, Publication 103: The 2007 Recommendations of the International Commission on Radiological Protection, 2007; adopted in Australia in ARPANSA, National Directory for Radiation Protection, retrieved 2026-08-18.

For the same absorbed dose, α radiation produces an equivalent dose twenty times larger than β or γ radiation, because its dense ionisation does far more damage to the cells it reaches. For example, an absorbed dose of $1\,\mathrm{Gy}$ from an α source corresponds to an equivalent dose of $20\,\mathrm{Sv}$, while $1\,\mathrm{Gy}$ from a γ source corresponds to $1\,\mathrm{Sv}$.

Effective dose — allowing for the sensitivity of the organ. Different organs and tissues have different sensitivities to radiation: the same equivalent dose to two different organs does not carry the same overall risk. The **tissue weighting factor** w_T represents the contribution of each organ to the total risk when the whole body is irradiated. The **effective dose** combines the equivalent doses to all the irradiated organs into a single number for the whole body:

$$E_{\mathrm{eff}} = \sum_T w_T H_T$$

where the sum is taken over all irradiated tissues T, and H_T is the equivalent dose received by tissue T. The unit of effective dose is also the sievert (Sv). The tissue weighting factors used in Australia are:

Tissue or organ	Tissue weighting factor w_T
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Breast	0.12
Remainder tissues (as a group)	0.12
Gonads	0.08
Bladder	0.04
Oesophagus	0.04
Liver	0.04
Thyroid	0.04
Bone surface	0.01
Brain	0.01
Salivary glands	0.01
Skin	0.01

Source: ICRP, Publication 103: The 2007 Recommendations of the International Commission on Radiological Protection, 2007; adopted in Australia in ARPANSA, National Directory for Radiation Protection, retrieved 2026-08-18.

The weighting factors add to 1, so if the whole body receives a uniform equivalent dose H, the effective dose equals H. Effective dose is the quantity used to compare very different exposures — a chest X-ray against a year of background radiation, for example — with a single number.

Doses in context. The table below places some familiar and regulated doses on the same scale. The Australian average dose from natural background radiation — from cosmic rays, from rocks and soil, and from radon — is about $1.5\,\mathrm{mSv}$ per year. The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA), based in Melbourne, is the Commonwealth authority that sets and monitors radiation protection standards in Australia. The **dose limits** below apply to exposure from regulated sources *above* natural background and medical exposure: the limit for members of the public is $1\,\mathrm{mSv}$ per year, and for radiation workers it is $20\,\mathrm{mSv}$ per year averaged over five years (and no more than $50\,\mathrm{mSv}$ in any single year).

Situation	Approximate effective dose
One chest X-ray	$0.02\,\mathrm{mSv}$
One year of natural background radiation (Australian average)	$1.5\,\mathrm{mSv}$
Annual dose limit for a member of the public (above background)	$1\,\mathrm{mSv}$
One CT scan of the abdomen	$10\,\mathrm{mSv}$
Annual dose limit for a radiation worker (averaged over five years)	$20\,\mathrm{mSv}$
Whole-body dose at which acute radiation syndrome can begin (received in a short time)	about $1\,\mathrm{Sv}$
Whole-body dose fatal to about half of those exposed without intensive treatment (received in a short time)	about $3–5\,\mathrm{Sv}$

Sources: ARPANSA, Radiation doses, retrieved 2026-08-18; ARPANSA, National Directory for Radiation Protection, retrieved 2026-08-18; WHO, Ionizing radiation: health effects, retrieved 2026-08-18. For the whole-body rows the radiation is γ radiation, for which $w_R = 1$, so the absorbed dose in gray is numerically equal to the equivalent dose in sievert.

Managing exposure. Radiation workers reduce their dose in three simple ways: spend less **time** near a source, keep a greater **distance** from it, and place **shielding** (such as lead or concrete) between the source and the body. Workers wear small **dosimeters** — badges containing material that records exposure — which are collected and read regularly to check that their dose stays within the limits. A dosimeter measures external exposure only; a worker who handles α-emitting sources must also follow procedures that prevent the source entering the body, because an external badge cannot detect internal exposure.

Worked examples

Example 1 — scaffolded

During a safety check at a hospital sterilisation unit, a $0.25\,\mathrm{kg}$ sample of tissue absorbs $6.0 \times 10^{-3}\,\mathrm{J}$ of energy from a γ source. Calculate the absorbed dose in gray and in milligray.

Working	Comment
$E = 6.0 \times 10^{-3}\,\mathrm{J}$, $m = 0.25\,\mathrm{kg}$.	List the data.
$D = \dfrac{E}{m} = \dfrac{6.0 \times 10^{-3}}{0.25}$.	Absorbed dose is energy deposited per kilogram.
$= 0.024\,\mathrm{Gy}$.	$1\,\mathrm{Gy} = 1\,\mathrm{J\,kg^{-1}}$.
$0.024\,\mathrm{Gy} = 24\,\mathrm{mGy}$.	$1\,\mathrm{Gy} = 1000\,\mathrm{mGy}$.

Example 2 — scaffolded

Two small samples of tissue each receive an absorbed dose of $3.0\,\mathrm{mGy}$, one from an α source and one from a γ source. Calculate the equivalent dose to each sample and compare the results.

Working	Comment
$D = 3.0\,\mathrm{mGy}$ for both samples; $w_R = 20$ (α), $w_R = 1$ (γ).	The radiation weighting factor depends on the type of radiation.
α sample: $H = w_R D = 20 \times 3.0 = 60\,\mathrm{mSv}$.	Equivalent dose in sievert.
γ sample: $H = w_R D = 1 \times 3.0 = 3.0\,\mathrm{mSv}$.	Same absorbed dose, different radiation.
The α sample receives twenty times the equivalent dose of the γ sample.	α radiation causes far more cell damage per gray of absorbed dose, because it ionises densely.

Example 3 — unscaffolded

Over one quarter, a technician working with radioactive sources receives an equivalent dose of $18\,\mathrm{mSv}$ to the lungs, $6.0\,\mathrm{mSv}$ to the thyroid and $25\,\mathrm{mSv}$ to the skin. Calculate the technician's effective dose for the quarter, and comment on how it compares with the annual dose limits.

The effective dose weights each organ's equivalent dose by the organ's sensitivity:

$$E_{\mathrm{eff}} = \sum_T w_T H_T .$$

Using the tissue weighting factors $w_T = 0.12$ (lung), 0.04 (thyroid) and 0.01 (skin):

$$E_{\mathrm{eff}} = (0.12 \times 18) + (0.04 \times 6.0) + (0.01 \times 25) = 2.16 + 0.24 + 0.25 = 2.65\,\mathrm{mSv} .$$

This is above the $1\,\mathrm{mSv}$ annual limit that applies to members of the public, but well within the occupational limit of $20\,\mathrm{mSv}$ per year that applies to radiation workers. (It is also less than twice the Australian average annual dose from natural background radiation, $1.5\,\mathrm{mSv}$.)

∴ the effective dose for the quarter is $2.65\,\mathrm{mSv}$, within the occupational limit.

Example 4 — unscaffolded

The average effective dose from natural background radiation in Australia is about $1.5\,\mathrm{mSv}$ per year. Approximating the background radiation as having $w_R = 1$, estimate the energy absorbed in one year by a $72\,\mathrm{kg}$ adult from natural background radiation, and comment on the result.

With $w_R = 1$, an effective dose of $1.5\,\mathrm{mSv}$ corresponds to an absorbed dose of about $D = 1.5\,\mathrm{mGy} = 1.5 \times 10^{-3}\,\mathrm{J\ kg^{-1}}$. Rearranging $D = E / m$:

$$E = D\,m = 1.5 \times 10^{-3} \times 72 = 0.108\,\mathrm{J} \approx 0.11\,\mathrm{J} .$$

This is a remarkably small amount of energy — about the energy needed to lift a $100\,\mathrm{g}$ apple through $11\,\mathrm{cm}$ (using $g = 9.8\,\mathrm{N\ kg^{-1}}$, $E_g = m\,g\,h = 0.10 \times 9.8 \times 0.11 \approx 0.11\,\mathrm{J}$). The biological significance of radiation is therefore not the total energy deposited but the way that energy arrives: concentrated into ionising events that break chemical bonds in cells.

∴ the absorbed energy is about $0.11\,\mathrm{J}$ per year.

Practice questions

Question 1 During an industrial radiography inspection, a $0.60\,\mathrm{kg}$ region of a technician's hand absorbs $9.0 \times 10^{-4}\,\mathrm{J}$ of energy from a sealed γ source. (a) State the formula relating absorbed dose, energy and mass. (b) Calculate the absorbed dose in gray. (c) Convert your answer to milligray.

Question 2 A small tissue sample receives an absorbed dose of $12\,\mathrm{mGy}$. (a) State the radiation weighting factor for β radiation. (b) Calculate the equivalent dose to the sample in millisievert if the dose came from a β source. (c) Calculate the equivalent dose if the same absorbed dose came from an α source instead.

Question 3 A patient's thyroid gland receives an equivalent dose of $40\,\mathrm{mSv}$. The tissue weighting factor for the thyroid is 0.04. (a) State what the tissue weighting factor represents. (b) Calculate the contribution of this dose to the patient's effective dose. (c) Compare your answer with the annual dose limit for a member of the public ($1\,\mathrm{mSv}$).

Question 4 A worker receives an equivalent dose of $15\,\mathrm{mSv}$ to the lungs and $10\,\mathrm{mSv}$ to the stomach. The tissue weighting factor is 0.12 for each organ. (a) Calculate the contribution of each organ to the effective dose. (b) Calculate the worker's total effective dose. (c) Explain why effective dose, rather than absorbed dose alone, is the better quantity for comparing the overall risks of different exposures.

Question 5 A radiation worker spends time in an area where the dose rate is $2.5\,\mu\mathrm{Sv}$ per hour. (a) Calculate the dose received during a 6.0-hour shift in this area. (b) Calculate how many such shifts would give a total dose of $1.0\,\mathrm{mSv}$.

Question 6 A $2.0\,\mathrm{kg}$ region of tissue receives an absorbed dose of $45\,\mathrm{mGy}$. (a) Calculate the energy absorbed by the region. (b) Explain how such a small amount of energy can nevertheless cause significant biological damage.

Question 7 A resident living near a licensed nuclear facility receives an additional effective dose of $0.32\,\mathrm{mSv}$ in one year from the facility's emissions, above natural background. (a) State whether this dose is within the annual dose limit for a member of the public, and justify your answer. (b) Express this dose as a fraction of the Australian average annual dose from natural background radiation ($1.5\,\mathrm{mSv}$).

Question 8 A worker accidentally inhales radioactive dust, and the lung tissue receives an absorbed dose of $0.80\,\mathrm{mGy}$ from α radiation. (a) Calculate the equivalent dose to the lung tissue. (b) Calculate the equivalent dose that the same absorbed dose would have produced if it had come from γ radiation instead. (c) Use your answers to explain why inhaled α-emitting dust is treated as a serious health hazard.

Question 9 Explain why an α source is the least hazardous of the three common radiations when it is held outside the body, but the most hazardous when the source is inside the body. Refer to the penetration and ionisation properties of α radiation.

Question 10 Explain why γ-emitting sources are the main external hazard in places where radioactive materials are used, and why thick lead or concrete shielding is used to store them. Compare with the behaviour of α and β radiation.

Question 11 Distinguish between the short-term effects of a high dose of radiation received over a short time, and the long-term effects of low doses. Give one example of each type of effect.

Question 12 A chest X-ray delivers an effective dose of about $0.02\,\mathrm{mSv}$ and a CT scan of the abdomen delivers about $10\,\mathrm{mSv}$. (a) Calculate how many chest X-rays would deliver the same effective dose as one abdominal CT scan. (b) A patient says "it's all just an X-ray, so a CT scan and a chest X-ray are the same". Use your answer to (a) to comment on this claim.

Question 13 A media report about a radiation facility states: "Workers were exposed to $5\,\mathrm{mSv}$ — five times the public dose limit." Critically evaluate this claim, using your knowledge of the public and occupational dose limits and of natural background radiation. You may assume the Australian average natural background dose is $1.5\,\mathrm{mSv}$ per year.

Question 14 In one year a radiation worker receives equivalent doses of $20\,\mathrm{mSv}$ to the red bone marrow, $20\,\mathrm{mSv}$ to the breast and $20\,\mathrm{mSv}$ to the thyroid. The tissue weighting factors are 0.12 (red bone marrow), 0.12 (breast) and 0.04 (thyroid). (a) Calculate the worker's effective dose for the year. (b) State whether this effective dose is within the annual occupational dose limit of $20\,\mathrm{mSv}$, and justify your answer.

Question 15 Radiation workers often wear a dosimeter badge on the outside of their clothing. Explain why such a badge would not record the dose from an internal α source, and state what additional precautions a workplace that handles α-emitting sources should take as a result.

Question 16 A $1.2\,\text{kg}$ region of tissue absorbs $3.6 \times 10^{-2}\,\text{J}$ of energy from a β source. (a) Calculate the absorbed dose in gray. (b) Calculate the equivalent dose in sievert.

Question 17 Radiation dose limits in Australia are set on the assumption that there is no dose of ionising radiation below which the risk of long-term effects is exactly zero. Explain what this assumption means for how the limits should be interpreted: does a dose below the limit have no effect, and does a dose above the limit guarantee harm?

Question 18 In 1987, in the city of Goiânia in Brazil, a discarded medical radiotherapy source containing caesium-137 — a strong γ emitter — was broken open, and several people were exposed to the unshielded source. One person received a whole-body equivalent dose of about $3.0\,\text{Sv}$ over several days. (a) State the radiation weighting factor for γ radiation, and hence state the absorbed dose this person received, in gray. (b) Using the dose ranges given in the theory, predict the likely short-term effects of this dose. (c) State the main long-term risk for someone who survives such an exposure.

Answers

Question 1 (b) $1.5\times10^{-3}\,\mathrm{Gy}$; (c) $1.5\,\mathrm{mGy}$. **Question 2** (a) 1; (b) $12\,\mathrm{mSv}$; (c) $240\,\mathrm{mSv}$. **Question 3** (b) $1.6\,\mathrm{mSv}$; (c) greater than the $1\,\mathrm{mSv}$ public annual limit. **Question 4** (a) lungs $1.8\,\mathrm{mSv}$, stomach $1.2\,\mathrm{mSv}$; (b) $3.0\,\mathrm{mSv}$. **Question 5** (a) $15\,\mu\mathrm{Sv}$; (b) about 67 shifts. **Question 6** (a) $0.090\,\mathrm{J}$. **Question 7** (a) yes, $0.32\,\mathrm{mSv}<1\,\mathrm{mSv}$; (b) about 0.21 (roughly one-fifth). **Question 8** (a) $16\,\mathrm{mSv}$; (b) $0.80\,\mathrm{mSv}$. **Question 9** Model answer in solutions. **Question 10** Model answer in solutions. **Question 11** Model answer in solutions. **Question 12** (a) 500; (b) see solutions. **Question 13** Model answer in solutions. **Question 14** (a) $5.6\,\mathrm{mSv}$; (b) yes, within $20\,\mathrm{mSv}$. **Question 15** Model answer in solutions. **Question 16** (a) $0.030\,\mathrm{Gy}$ ($30\,\mathrm{mGy}$); (b) $0.030\,\mathrm{Sv}$ ($30\,\mathrm{mSv}$). **Question 17** Model answer in solutions. **Question 18** (a) $w_R=1$; $D=3.0\,\mathrm{Gy}$; (b), (c) see solutions.

Fully-worked solutions

Question 1 $E=9.0\times10^{-4}\,\mathrm{J}$, $m=0.60\,\mathrm{kg}$. (a) $D=\dfrac{E}{m}$, where D is the absorbed dose, E the energy deposited and m the mass irradiated. (b) $D=\dfrac{9.0\times10^{-4}}{0.60}=1.5\times10^{-3}\,\mathrm{Gy}$. (c) $1.5\times10^{-3}\,\mathrm{Gy}=1.5\,\mathrm{mGy}$.

Question 2 $D=12\,\mathrm{mGy}$. (a) The radiation weighting factor for β radiation is $w_R=1$. (b) $H=w_R D=1\times12=12\,\mathrm{mSv}$. (c) For α radiation $w_R=20$, so $H=20\times12=240\,\mathrm{mSv}$.

Question 3 $H=40\,\mathrm{mSv}$, $w_T=0.04$ (thyroid). (a) The tissue weighting factor represents the relative contribution of that organ to the total health risk when the whole body is irradiated; it reflects how sensitive the organ is to radiation. (b) Contribution to effective dose $=w_T H_T=0.04\times40=1.6\,\mathrm{mSv}$. (c) $1.6\,\mathrm{mSv}$ is greater than the annual dose limit for a member of the public ($1\,\mathrm{mSv}$). (Note that medical exposures are managed separately from the public dose limit, which applies to exposure from regulated sources.)

Question 4 $H=15\,\mathrm{mSv}$ (lungs), $H=10\,\mathrm{mSv}$ (stomach), $w_T=0.12$ for each. (a) Lungs: $0.12\times15=1.8\,\mathrm{mSv}$. Stomach: $0.12\times10=1.2\,\mathrm{mSv}$. (b) $E_{\mathrm{eff}}=1.8+1.2=3.0\,\mathrm{mSv}$. (c) Absorbed dose only measures the energy deposited per kilogram; it does not distinguish between radiation types (which cause different amounts of damage per gray) or between organs (which have different sensitivities). Equivalent dose allows for the radiation type and effective dose also allows for the organs irradiated, so effective dose is the quantity that best represents the overall risk to the person and allows different exposures to be compared directly.

Question 5 Dose rate $=2.5\,\mu\mathrm{Sv}$ per hour. (a) Dose $=2.5\times6.0=15\,\mu\mathrm{Sv}$. (b) $1.0\,\mathrm{mSv}=1000\,\mu\mathrm{Sv}$. Number of shifts $=\dfrac{1000}{15}=66.7$, so about 67 shifts (the worker would exceed $1.0\,\mathrm{mSv}$ during the 67th shift).

Question 6 $m=2.0\,\mathrm{kg}$, $D=45\,\mathrm{mGy}=45\times10^{-3}\,\mathrm{J\,kg^{-1}}$. (a) $E=Dm=45\times10^{-3}\times2.0=0.090\,\mathrm{J}$. (b) The damage from radiation is not caused by heating but by ionisation: the deposited energy arrives in concentrated events that knock electrons out of atoms, break chemical bonds and can damage the DNA in cells. Even a small total energy, delivered this way, can kill cells or leave mutations that may later lead to cancer.

Question 7 Additional dose $=0.32\,\mathrm{mSv}$. (a) The annual dose limit for a member of the public is $1\,\mathrm{mSv}$ (above natural background and medical exposure). Since $0.32\,\mathrm{mSv}<1\,\mathrm{mSv}$, the dose is within the limit. (b) $\dfrac{0.32}{1.5}=0.213$, so the dose is about 0.21, or roughly one-fifth, of the average annual natural background dose.

Question 8 $D=0.80\,\mathrm{mGy}$. (a) For α radiation $w_R=20$: $H=20\times0.80=16\,\mathrm{mSv}$. (b) For γ radiation $w_R=1$: $H=1\times0.80=0.80\,\mathrm{mSv}$. (c) The same absorbed dose from α radiation gives twenty times the equivalent dose, because α particles ionise densely and cause much more cell damage per gray. Inside the lung there is no dead outer skin layer to stop the α radiation, so all of its energy is deposited in sensitive living tissue. This is why inhaled α-emitting dust is treated as a serious hazard even when the absorbed dose seems small.

Question 9 Model answer (4 marks: 1 mark for each of penetration outside, ionisation outside, penetration inside, ionisation inside). Outside the body, α radiation is stopped by the dead outer layer of skin (and by a few centimetres of air), so it does not reach the living cells beneath and causes little damage. Its low penetration makes it the least hazardous radiation externally. Inside the body the situation reverses: there is no protective dead layer between the source and the living cells, and the α particles deposit all of their energy in a very short track through living tissue. Because α radiation ionises very densely, this concentrated energy causes severe local cell damage, making α sources the most hazardous of the three when inside the body.

Question 10 Model answer (3 marks: 1 mark for γ penetration, 1 mark for α/β contrast, 1 mark for shielding). γ radiation is highly penetrating: it passes through the skin and reaches the internal organs, so an external γ source can irradiate the whole body. α radiation is stopped by the dead outer layer of skin and β radiation penetrates only millimetres into tissue, so neither reaches the internal organs from outside. Because γ radiation is so penetrating, storing and shielding γ sources requires dense material — thick lead or concrete — to absorb the radiation and reduce the dose rate to safe levels.

Question 11 Model answer (4 marks: 1 mark for each of the two comparisons, 1 mark for each example). A high dose received over a short time kills large numbers of cells at once, so the tissue shows visible damage soon after the exposure; these effects have a threshold dose below which they do not occur, and their severity increases with dose. An example is acute radiation syndrome (nausea, vomiting, damage to the bone marrow and blood), which can follow a whole-body dose of about $1\,\text{Sv}$ or more. Low doses do not kill enough cells to cause immediate illness, but they can leave mutated cells, increasing the probability that the person develops cancer years or decades later; the probability, not the severity, increases with dose. An example is the increased lifetime risk of cancer following repeated low-dose exposures.

Question 12 Chest X-ray $= 0.02\,\text{mSv}$; abdominal CT $= 10\,\text{mSv}$. (a) Number of chest X-rays $= \dfrac{10}{0.02} = 500$. (b) The claim is not supported. One abdominal CT scan delivers about 500 times the effective dose of a single chest X-ray — about $10\,\text{mSv}$, roughly seven times the Australian average annual background dose of $1.5\,\text{mSv}$. Although both use X-rays, the doses differ enormously, so the risks cannot be treated as "the same". (Medical imaging is still justified when the benefit to the patient outweighs the small added risk.)

Question 13 Model answer (4 marks: 1 mark for comparing with the occupational limit, 1 mark for comparing with the public limit, 1 mark for comparing with background, 1 mark for an overall evaluation of the claim). The claim is technically correct but misleading. The public dose limit is $1\,\text{mSv}$ per year, so $5\,\text{mSv}$ is indeed five times that limit — but the public limit does not apply to radiation workers, whose occupational limit is $20\,\text{mSv}$ per year (averaged over five years). A dose of $5\,\text{mSv}$ is one-quarter of the occupational limit, so a worker receiving it would still be within the regulated working limits. For context, $5\,\text{mSv}$ is also only about three times the Australian average annual dose from natural background radiation ($1.5\,\text{mSv}$), which everyone receives. The headline invites the reader to treat any exceedance of the public limit as dangerous, when the relevant limit for workers is four times higher and the dose itself is well below the doses at which any immediate effects occur.

Question 14 $H = 20\,\text{mSv}$ to each of three organs; $w_T = 0.12$ (red bone marrow), 0.12 (breast), 0.04 (thyroid). (a) $E_{\text{eff}} = (0.12 \times 20) + (0.12 \times 20) + (0.04 \times 20) = 2.4 + 2.4 + 0.8 = 5.6\,\text{mSv}$. (b) The occupational dose limit is $20\,\text{mSv}$ per year (averaged over five years). Since $5.6\,\text{mSv} < 20\,\text{mSv}$, the dose is within the occupational limit.

Question 15 Model answer (3 marks: 1 mark for why the badge misses internal α exposure, 1 mark for the penetration point, 1 mark for precautions). A dosimeter worn outside the clothing measures only radiation that reaches it from outside the body. α radiation cannot penetrate even the outer layer of skin or the badge's covering, and an internal α source irradiates the organs from the inside, so no radiation from it reaches the badge and the badge records nothing. A workplace handling α-emitting sources must therefore prevent the source entering the body: sealed containers and enclosed handling, good ventilation, no eating or drinking in the area, protective clothing and gloves, and monitoring for contamination of surfaces, air and workers (for example, checks for inhaled or ingested material), rather than relying on the external badge alone.

Question 16 $m = 1.2\,\text{kg}$, $E = 3.6 \times 10^{-2}\,\text{J}$. (a) $D = \dfrac{E}{m} = \dfrac{3.6 \times 10^{-2}}{1.2} = 0.030\,\text{Gy}$ $(= 30\,\text{mGy})$. (b) For β radiation $w_R = 1$, so $H = 1 \times 0.030 = 0.030\,\text{Sv}$ $(= 30\,\text{mSv})$.

Question 17 Model answer (4 marks: 1 mark for the meaning of the assumption, 1 mark for "below the limit", 1 mark for "above the limit", 1 mark for the purpose of the limits). The assumption means that the risk of long-term effects (such as cancer) is taken to increase with dose at every level, with no completely safe threshold. A dose *below* the limit therefore does not have "no effect": it still carries a small risk; the limit is not a boundary between "safe" and "unsafe" but a line set to keep the added risk acceptably small. Conversely, a dose *above* the limit does not guarantee harm: long-term effects are a matter of probability, not certainty, and for high-dose effects with thresholds (such as acute radiation syndrome), harm occurs only once the threshold dose is exceeded. The limits are best understood as the level of exposure a regulator judges acceptable, set well below the doses at which immediate effects occur, rather than as a statement that nothing happens below them and harm is certain above them.

Question 18 Whole-body equivalent dose $H=3.0\,\mathrm{Sv}$ from γ radiation. (a) For γ radiation, $w_R=1$. Since $H=w_R D$, the absorbed dose is $D=\frac{H}{w_R}=\frac{3.0}{1}=3.0\,\mathrm{Gy}$. (b) A whole-body dose of $3.0\,\mathrm{Gy}$ lies in the $2–6\,\mathrm{Gy}$ range associated with severe acute radiation syndrome: nausea and vomiting within hours, followed by damage to the bone marrow and blood, hair loss and internal bleeding. Without intensive medical treatment, doses of roughly $3–5\,\mathrm{Gy}$ are fatal to about half of those exposed. (These dose ranges apply to doses received in a short time; because this dose was received over several days, the body had some time to repair damage between exposures, and the effects would be less severe than for the same dose received all at once.) (c) The main long-term risk for a survivor is an increased probability of developing cancer years or decades later.

Scope — *VCE Physics Study Design, Unit 1, Area of Study 2*: “evaluate the use of medical radioisotopes in therapy including the effects on healthy and damaged tissues and cells”.

Theory

Treating disease with radiation from the nucleus. Section 3E examined what ionising radiation does to the human body — mostly harm. The same physics can be turned to a patient’s advantage. Radiation that breaks up molecules inside living cells can be aimed, in carefully planned doses, at diseased tissue, killing the diseased cells while the surrounding healthy tissue survives and recovers. This is the basis of **radioisotope therapy**, the medical use of radioactive isotopes to treat disease — above all cancer, in which cells divide out of control. More than 150,000 Australians are diagnosed with cancer each year, and radiation treatment is one of the three main weapons against the disease, alongside surgery and drug treatments. Source: Cancer Council Australia, Cancer facts & figures 2024, retrieved 2026-08-18.

In Australia, medical radioisotopes are manufactured by ANSTO at its OPAL research reactor at Lucas Heights, New South Wales, and supplied to hospitals around the country. Source: ANSTO, Medical radioisotopes, ansto.gov.au, retrieved 2026-08-18.

Why radiation kills diseased cells. Ionising radiation knocks electrons out of the atoms it passes through (Section 3B). In living tissue those ionisations break chemical bonds. The critical target is the DNA in the cell nucleus: a cell whose DNA is badly damaged either dies outright or loses the ability to divide. A tumour is a population of dividing cells, so enough damage to its DNA makes the tumour stop growing and shrink.

The difference between diseased and healthy tissue is one of degree, not of kind. Cells that divide rapidly are the most sensitive to ionising radiation, and cancer cells divide rapidly and are poor at repairing the damage. Most healthy cells divide slowly and repair themselves well, so they survive a dose that kills the tumour. But some healthy cells — in the skin, the gut lining and the blood — also divide quickly, and they are always affected to some extent. Every treatment is therefore a balance: as much damage as possible to the diseased cells, as little as possible to the healthy ones.

Choosing a radioisotope: the type of radiation. The penetrating power of each radiation type, studied in Section 3B, sets what it can do in therapy:

- **α particles** are stopped by a few cells’ thickness of tissue. Their ionisation is dense but deposited in a tiny volume — useless from outside the body, powerful if the source sits right against the diseased cells.
- **β^- particles** travel a few millimetres in tissue. A β^- emitter soaked up by a tumour irradiates the tumour while largely sparing tissue beyond it.
- **γ rays** pass through the body. Only γ radiation can deliver a dose from a source outside the body to a tumour deep inside — but the same penetrating power means γ rays also pass through healthy tissue on the way in and on the way out.

Choosing a radioisotope: the half-life. The half-life (Section 3C) must suit the job. The isotope must live long enough to be manufactured, transported to the hospital and delivered to the patient, and it must keep emitting while the treatment is given. But a therapy isotope inside a patient should also decay away reasonably quickly, so the patient does not remain dangerously radioactive for years. Iodine-131, with a half-life of 8.0 days, is almost gone within a few weeks — a good match for a treatment. An external source in a machine, by contrast, is allowed a much longer half-life, because a slowly decaying source gives a steady output for years between replacements.

Choosing a radioisotope: targeting the diseased tissue. The cleanest way to concentrate the dose on diseased tissue is to let the body do the delivering. Some elements are collected by only certain tissues: the thyroid gland needs iodine to make its hormones and actively collects iodine from the blood, so radioactive iodine swallowed by a patient ends up concentrated in thyroid tissue. Radium behaves chemically like calcium and is laid down in bone. If the diseased cells share that chemistry, the radioisotope finds them by itself.

The table lists the therapy radioisotopes used in this subtopic.

Radioisotope	Radiation that does the therapy work	Half-life $t_{1/2}$	Example therapy use
cobalt-60	γ rays (1.17 and 1.33 MeV)	5.27 years	external beams aimed at tumours; radiosurgery of the brain
iridium-192	γ rays (with β^-)	73.8 days	sealed sources placed briefly inside or next to a tumour
iodine-131	β^- particles (with γ rays)	8.0 days	thyroid cancer; overactive thyroid gland
lutetium-177	β^- particles (with γ rays)	6.6 days	targeted treatment of some advanced cancers
radium-223	α particles	11.4 days	prostate cancer that has spread into the bones

Source: IAEA, LiveChart of Nuclides, retrieved 2026-08-18.

Delivery method 1 — external beams. The source stays outside the body and its γ rays are aimed at the tumour. Cobalt-60 was for decades the standard isotope for this work: a lump of cobalt-60 in a shielded machine emits penetrating γ rays that reach tumours anywhere in the body. Most modern Australian clinics now use electrically powered machines that produce X-rays without any radioactive source, but cobalt-60 is still used in specialised radiosurgery devices that focus many weak γ-ray beams from separate cobalt-60 sources onto one small spot inside the brain.

Whichever machine is used, the geometry is the same idea: several weak beams enter the body from different directions and cross at the tumour. Each beam gives only a small dose to the healthy tissue along its path, but the tumour, sitting at the crossing point, receives the sum of all the beams.

Delivery method 2 — sealed sources placed inside the body. In **brachytherapy** (internal radiotherapy with a sealed source), a small sealed capsule or wire of a radioisotope such as iridium-192 is placed directly inside or next to the tumour, often for only a few minutes at a time. Because the source touches the target, the tumour receives a very large dose while the dose falls away rapidly with distance, sparing tissue further away. Afterwards the sealed source is removed: nothing radioactive is left behind, and the patient is not a radiation source to the people around them.

Delivery method 3 — radioisotopes swallowed or injected. The patient takes an unsealed radioisotope into the body, and the body's own chemistry carries it to the diseased tissue. The classic example is iodine-131, swallowed as a capsule or drink to treat thyroid cancer and an overactive thyroid gland. The thyroid collects iodine from the blood more actively than any other tissue, so the iodine-131 concentrates there; the β^- particles it emits then irradiate the thyroid tissue from within, travelling only far enough to cover the gland. The γ rays given off at the same time escape the body — which is why a treated patient is briefly radioactive to others — and also let doctors check where the iodine has gone. Newer treatments attach radioisotopes to designer molecules that seek out particular tumour cells: lutetium-177 (β^-, $t_{1/2} = 6.6$ days) is carried to some advanced cancers this way, and radium-223 (α, $t_{1/2} = 11.4$ days) is laid down in bone to attack prostate cancer that has spread there.

Effects on damaged tissue. In the tumour, the radiation breaks DNA faster than the cancer cells can repair it. The cells stop dividing and die, the tumour shrinks, and the disease is cured or at least brought under control; where a cure is not possible, shrinking the tumour still relieves the symptoms it causes.

Effects on healthy tissue, and how they are managed. Healthy tissue near the treatment receives some dose whatever is done. Early effects — reddened skin in the beam path, tiredness, an upset stomach — resemble a sunburn or a mild illness and usually pass once treatment ends. The long-term effects studied in Section 3E also apply: years later there is a small additional risk of a second cancer caused by the scattered dose to healthy cells. The whole art of radiotherapy is managing this trade-off, and the main tools are physical:

- **Choice of radiation and half-life** — a short-range emitter and a half-life matched to the treatment keep the dose inside the target and inside the treatment period.

- **Targeting** — an element the diseased tissue collects by itself (iodine for thyroid, radium for bone) puts the source in the tumour and almost nowhere else.
- **Beam geometry** — many weak beams crossing at the tumour spread the dose along each beam's path over a large volume of healthy tissue.
- **Fractionation** — giving the total dose in many small daily portions (fractions) over several weeks rather than all at once. Healthy cells repair the damage of each fraction between sessions; cancer cells, poor at repair, cannot fix the damage, and it builds up until they die.
- **Time, distance and shielding** — for staff and visitors near a patient who has swallowed or been injected with a radioisotope: keep visits short, stand well back, and use shielding where practical. Hospitals give such patients simple contact rules for the first days, while the isotope decays and the body passes the unused portion out.

Evaluating radioisotope therapy. "Evaluate" means weighing benefit against risk on the physics of the case. The benefit: a planned, concentrated dose can cure or control a disease that would otherwise be fatal. The risks: unavoidable dose to healthy tissue now, and the small long-term risk of a radiation-induced cancer later. The same radiation that *causes* cancer at uncontrolled doses *cures* cancer at controlled ones — the difference is the dose, the targeting and the planning. Physicists contribute exactly that control: choosing the isotope (radiation type, half-life, targeting chemistry), calculating the absorbed dose (Section 3E) and designing the geometry, shielding and safety rules. Radioisotopes are also used to *image* disease rather than treat it; that application is studied in Option 2.6 (Section 10E).

Worked examples

Example 1 — scaffolded

ANSTO supplies iodine-131 ($t_{1/2} = 8.0$ days) for thyroid therapy. A hospital receives a shipment and prepares a patient's capsule 16 days later. Calculate the fraction of the iodine-131 remaining when the capsule is prepared, and the fraction that has decayed.

Working	Comment
$t_{1/2} = 8.0$ days; elapsed time $= 16$ days.	List the data.
Number of half-lives $= \dfrac{16}{8.0} = 2.0$.	Whole half-lives, as modelled in Section 3C.
Fraction remaining $= \left(\dfrac{1}{2}\right)^2 = \dfrac{1}{4}$.	The amount halves once per half-life.
Fraction decayed $= 1 - \dfrac{1}{4} = \dfrac{3}{4}$.	What has not remained has decayed.

The hospital must allow for this decay when it plans how much iodine-131 to order and when to treat the patient.

Example 2 — scaffolded

During a course of internal radiotherapy, a thyroid tumour of mass 25 g receives a total absorbed dose of 60 Gy. (a) Calculate the energy deposited in the tumour. (b) A cup of hot tea holds far more energy than your answer. Explain why such a small energy can have such a large biological effect.

Recall from Section 3E: absorbed dose is energy deposited per unit mass, $D = \dfrac{E}{m}$, with $1\,\text{Gy} = 1\,\text{J kg}^{-1}$.

Working	Comment
$D = 60$ Gy; $m = 25\,\text{g} = 0.025\,\text{kg}$.	Convert mass to kilograms — the gray is J kg^{-1}.
$E = D\,m = 60 \times 0.025$.	Rearrange $D = \dfrac{E}{m}$.

Working	Comment
$= 1.5\,\mathrm{J}$.	Evaluate.
(b) The energy arrives as ionising radiation, not as heat.	Each particle or photon breaks chemical bonds along its track.
A few ionisations in a cell's DNA can kill the cell or stop it dividing.	Damage is concentrated at the molecular level, in the cells of the tumour.

Example 3 — unscaffolded

A radiosurgery unit uses cobalt-60 sources ($t_{1/2} = 5.27$ years). Calculate the fraction of the cobalt-60 remaining after 10.5 years, and explain why the hospital must plan to replace the sources.

10.5 years is about two half-lives of cobalt-60 ($2 \times 5.27 = 10.54$ years), so the fraction remaining is

$$\left(\frac{1}{2}\right)^2 = \frac{1}{4}.$$

With only a quarter of the cobalt-60 nuclei left, there are far fewer decays each second and far fewer γ rays emitted each second: the source delivers its dose about four times more slowly than when new. Treatments would take about four times as long, and a patient who must hold still for a brain treatment is at greater risk if the session drags out. The hospital therefore replaces the sources on a schedule, long before they have fully decayed — a consequence of choosing a radioisotope rather than an electrically powered machine.

Example 4 — unscaffolded

A patient has thyroid cancer cells left after surgery. The treatment must reach thyroid tissue anywhere in the body, delivered from inside the body. The candidates are:

Isotope	Radiation	$t_{1/2}$
cobalt-60	γ	5.27 years
iodine-131	β^- and γ	8.0 days
radium-223	α	11.4 days

Select the best isotope and justify the choice, and explain why each of the other two is unsuitable.

Iodine-131 is the suitable isotope. The thyroid gland collects iodine from the blood to make its hormones, so swallowed iodine-131 concentrates itself in thyroid tissue wherever that tissue is — the body delivers the source to the diseased cells. Its β^- particles travel only a few millimetres, so their dose is deposited almost entirely in the thyroid tissue that absorbed the iodine. Its half-life of 8.0 days is long enough for the iodine to be taken up and deliver its dose, yet short enough that after a few weeks very little radioactivity remains in the patient.

Cobalt-60 is unsuitable: no part of the body collects cobalt, so a circulating cobalt-60 source would irradiate the whole body rather than the thyroid, and its penetrating γ rays would also expose everyone near the patient. Its 5.27-year half-life would keep the patient radioactive for far too long. **Radium-223 is unsuitable:** radium behaves like calcium and is laid down in bone, not collected by thyroid tissue, so it would not reach the target; its α particles, though powerful at very short range, are exactly suited to bone disease, not to thyroid therapy.

Practice questions

Question 1 A capsule of iodine-131 ($t_{1/2} = 8.0$ days) is prepared for a patient with an overactive thyroid gland. (a) Calculate the fraction of the iodine-131 remaining 24 days after preparation. (b) Calculate the fraction that has decayed in that time. (c) Explain why the hospital must know the half-life when it plans the treatment.

Question 2 Radiotherapy relies on diseased and healthy tissue responding differently to the same radiation. (a) Explain why cancer cells are generally more sensitive to ionising radiation than most healthy cells. (b) Healthy tissue is still damaged during treatment. Identify one type of healthy tissue that is affected and explain why it is affected. (c) Explain why the difference between cancer cells and healthy cells is described as a difference of degree, not of kind.

Question 3 A cobalt-60 source ($t_{1/2} = 5.27$ years) is used in a machine that aims γ rays at tumours from outside the body. (a) Calculate the fraction of the cobalt-60 remaining after 15.8 years. (b) Explain why the radiation from the source must be penetrating to be useful in this machine. (c) Explain why the source emits fewer γ rays each second as it gets older.

Question 4 Match radiation types to therapy roles, with physics reasons. (a) Explain why an external-beam machine must use a source that emits γ rays rather than α or β^- radiation. (b) Explain why a β^- emitter is often a good choice for a radioisotope that is swallowed or injected and absorbed by the diseased tissue. (c) Explain why an α emitter is useless as an external source but valuable once it is inside the body, in contact with diseased tissue.

Question 5 A tumour of mass 40 g receives a total absorbed dose of 50 Gy during a course of treatment. (a) Calculate the energy deposited in the tumour. (b) Suppose that same energy were spread evenly through 2.0 kg of healthy tissue. Calculate the absorbed dose to that tissue. (c) In real treatment the beam is aimed from several directions that cross at the tumour. Use your answers to explain why this geometry protects healthy tissue.

Question 6 A patient who has swallowed iodine-131 is given these rules for the first few days: keep your distance from other people, keep visits short, avoid close contact with children and pregnant women, and drink plenty of fluids. Explain the physics behind each rule.

Question 7 Sealed iridium-192 sources ($t_{1/2} = 73.8$ days) are used in brachytherapy. (a) Calculate the fraction of the iridium-192 remaining in a source 147.6 days after it was manufactured. (b) Calculate the time, in days, for a source to decay to one-eighth of its original amount.

Question 8 In brachytherapy a sealed iridium-192 source is placed inside the body next to the tumour for a few minutes and then removed. (a) Explain why the dose to the tumour is very large while the dose to tissue a few centimetres away is much smaller. (b) Explain why the patient is not left radioactive after the source is taken out.

Question 9 A sample of lutetium-177 ($t_{1/2} = 6.6$ days) must be stored until only one-sixteenth of the original amount remains. Calculate how long the sample must be stored.

Question 10 A total dose of 60 Gy is given as 30 small daily fractions over six weeks rather than in one large dose. Explain, in terms of healthy and damaged tissue, why fractionation is used.

Question 11 In a treatment, 0.80 J of radiation energy is deposited in a tumour of mass 20 g; the same energy, spread out, is deposited in 0.40 kg of surrounding healthy tissue. (a) Calculate the absorbed dose to the tumour. (b) Calculate the absorbed dose to the healthy tissue. (c) Compare the two doses and explain what this comparison shows about concentrating the radiation.

Question 12 Explain why iodine-131 is an effective treatment for disease of the thyroid gland but would be of no use against a cancer of, say, the lung, referring to how the isotope reaches the diseased tissue.

Question 13 Radium-223 ($t_{1/2} = 11.4$ days) is used to treat prostate cancer that has spread into the bones. (a) Calculate the fraction of a radium-223 sample remaining after 45.6 days. (b) Radium behaves chemically like calcium. Explain why this makes radium-223 suitable for treating cancers in bone, and why the α radiation it emits is an advantage in this role.

Question 14 A student says: “Treating cancer with radiation makes no sense. Radiation causes cancer.” Evaluate this statement, presenting the strongest case for and against it before reaching a conclusion.

Question 15 A patient is treated with iodine-131 ($t_{1/2} = 8.0$ days). (a) Calculate the fraction of the iodine-131 remaining in the patient’s body 32 days after treatment, ignoring any that the body has passed out. (b) Use your answer to explain why the patient’s contact rules last only a few weeks rather than being permanent.

Question 16 An external-beam treatment aims several weak γ-ray beams at a tumour from different directions. Draw a diagram of a body cross-section showing at least four beams crossing at the tumour, and use your diagram to explain why the tumour receives a large dose while each patch of skin where a beam enters receives only a small one.

Question 17 Over a year of work, a radiation worker's whole body (mass 70 kg) receives an absorbed dose of 0.020 Gy from scattered radiation. (a) Calculate the total energy absorbed by the worker's body. (b) Example 2 found 1.5 J deposited in a 25 g tumour. Your answer is of the same size, yet the worker's dose is harmless while the tumour's is cell-killing. Explain the difference.

Question 18 Section 3E stated that α radiation is barely hazardous when its source is outside the body but among the most damaging radiations when the source is inside the body. Explain both halves of that statement, and then explain how radium-223 therapy turns it to a patient's advantage.

Question 19 Two sealed sources are prepared, each with the same initial amount of a different isotope: iodine-131 ($t_{1/2}$=8.0 days) and cobalt-60 ($t_{1/2}$=5.27 years). (a) Calculate the fraction of each source that has decayed after 32 days. For cobalt-60, note that 32 days is far less than one half-life and state what this implies. (b) Which source delivers most of its radiation quickly? Explain why the answer matters when choosing between the two isotopes for different therapy jobs.

Question 20 Evaluate the use of iodine-131 in the treatment of thyroid cancer. In your answer, refer to the properties that make it suitable, and to its effects on both healthy and damaged tissue.

Answers

Question 1 (a) $\frac{1}{8}$; (b) $\frac{7}{8}$; (c) the amount of isotope falls as it decays, so the planned dose must allow for decay between manufacture and treatment. **Question 2** (a) cancer cells divide rapidly, and rapidly dividing cells are the most sensitive to ionising radiation; (b) for example the skin, gut lining or blood — these healthy cells also divide rapidly and so are damaged too; (c) healthy cells are damaged as well, but they divide more slowly and repair the damage better. **Question 3** (a) $\frac{1}{8}$; (b) only penetrating γ radiation can pass from outside the body to a tumour deep inside; α and β^- are stopped before they get there; (c) as cobalt-60 decays, fewer nuclei remain, so fewer decays occur each second and fewer γ rays are emitted. **Question 4** (a) only γ rays penetrate from outside the body to a deep tumour; α is stopped by the skin and β^- by a few millimetres of tissue; (b) β^- particles travel only a few millimetres, so their dose stays in the tissue that absorbed the isotope; (c) α particles cannot penetrate the skin from outside, but inside the body their dense ionisation over a few cells' thickness is concentrated on the diseased tissue they touch. **Question 5** (a) 2.0 J; (b) 1.0 Gy; (c) the tumour sits in every beam and receives the full summed dose, while each patch of healthy tissue lies in only one weak beam. **Question 6** Distance weakens the radiation reaching another person; shorter visits give a smaller dose; children and unborn babies have rapidly dividing cells and are more sensitive; fluids help the body pass unused iodine out sooner, shortening the time the patient is radioactive. **Question 7** (a) $\frac{1}{4}$; (b) 221.4 days. **Question 8** (a) the radiation is absorbed as it travels through tissue, so the dose falls off rapidly with distance from the source; (b) the sealed source is removed and no radioisotope has been taken into the body's tissues. **Question 9** 26.4 days. **Question 10** Between fractions, healthy cells repair the damage; cancer cells repair poorly and the damage builds up, so the net effect favours destruction of the tumour. **Question 11** (a) 40 Gy; (b) 2.0 Gy; (c) the tumour's dose is 20 times larger — concentrating the same energy in a small mass raises the dose in that proportion. **Question 12** The thyroid actively collects iodine to make its hormones, so swallowed iodine-131 concentrates in thyroid tissue and irradiates it from within; a lung cancer does not collect iodine, so the isotope would pass through without concentrating there. **Question 13** (a) $\frac{1}{16}$; (b) because it behaves like calcium, radium is laid down in bone where the cancer is; its α particles travel only a few cells' thickness, so their dense dose stays in the cancer cells near where the radium sits. **Question 14** See worked solution — the statement names a real risk but ignores dose, targeting and the benefit of treating an existing cancer. **Question 15** (a) $\frac{1}{16}$; (b) after four half-lives only a small fraction remains, so the dose rate to people nearby is small and the rules can end. **Question 16** Four or more weak beams cross at the tumour; the tumour receives the sum of all the beams, while each skin entry point receives only one weak beam. **Question 17** (a) 1.4 J; (b) the worker's energy is spread through 70 kg of tissue (a tiny dose), while the tumour's 1.5 J is concentrated in 25 g — dose, not energy alone, sets the biological effect. **Question 18** Outside the body α is stopped by the dead outer layer of skin and never reaches living cells; inside, it ionises densely across the living cells next to the source. Radium-223 is laid down in bone, so its α dose lands exactly on the cancer cells there and barely reaches anything else. **Question 19** (a) iodine-131: $\frac{15}{16}$ decayed; cobalt-60: 32 days is about $\frac{1}{60}$ of its half-life, so only a very small fraction (about 1%) has decayed and nearly all remains; (b) iodine-131 delivers its radiation quickly — suited to a short internal treatment, while cobalt-60's nearly steady output suits a machine used for years. **Question 20** See worked solution — suitable isotope choice justified; benefits to damaged tissue weighed against unavoidable dose to healthy tissue.

Fully-worked solutions

Question 1 $t_{1/2} = 8.0$ days. (a) 24 days is $\frac{24}{8.0} = 3$ half-lives, so the fraction remaining is $\left(\frac{1}{2}\right)^3 = \frac{1}{8}$. (b) Fraction decayed $= 1 - \frac{1}{8} = \frac{7}{8}$. (c) The amount of iodine-131 falls as it decays. If the hospital knows the half-life it can work out how much remains at any date, order the right amount from ANSTO, and schedule the treatment so the patient receives the planned dose.

Question 2 (a) Ionising radiation damages the DNA of dividing cells most effectively. Cancer cells divide rapidly and are poor at repairing the damage, so a dose of radiation kills them more readily than most healthy cells, which divide slowly and repair well. (b) Healthy tissues whose cells also divide rapidly — the skin, the lining of the gut and the blood — are sensitive for the same reason and are damaged during treatment. This is why patients get side effects such as reddened skin and tiredness. (c) “A difference of degree, not of kind” means healthy cells are not immune — they are damaged too. They are simply damaged *less* than cancer cells at the same dose, because they divide more slowly and repair better. There is no dose that kills only diseased cells, so every treatment is a balance.

Question 3 $t_{1/2} = 5.27$ years. (a) 15.8 years is $\frac{15.8}{5.27} = 3.0$ half-lives, so the fraction remaining is $\left(\frac{1}{2}\right)^3 = \frac{1}{8}$. (b) The source sits outside the patient but the tumour is inside. Only γ radiation is penetrating enough to pass through the body’s outer tissue and reach a deep tumour; α particles are stopped by the skin and β^- particles by a few millimetres of tissue. (c) The γ rays come from the decay of cobalt-60 nuclei. As time passes, fewer undecayed nuclei remain, so fewer decays happen each second and the source emits fewer γ rays each second.

Question 4 (a) An external source must irradiate tissue deep inside the body. γ rays penetrate the whole body and reach the tumour; α particles are stopped by the dead outer skin and β^- particles by the first few millimetres of tissue, so neither could reach a deep tumour from outside. (b) Once the isotope is absorbed by the diseased tissue, its β^- particles travel only a few millimetres before stopping. Their dose is therefore deposited almost entirely in the diseased tissue that took up the isotope, with little dose to tissue further away. (c) From outside the body, α particles are stopped by the dead outer layer of skin and deposit no dose in living tissue at all — useless. Inside the body, in direct contact with diseased tissue, that same short range is a strength: all of the α particle’s dense ionisation is dumped into the few diseased cells nearest the source, sparing everything beyond them.

Question 5 $m = 40\,\mathrm{g} = 0.040\,\mathrm{kg}$, $D = 50$ Gy. (a) $E = D\,m = 50 \times 0.040 = 2.0\,\mathrm{J}$. (b) $D = \frac{E}{m} = \frac{2.0}{2.0} = 1.0$ Gy. (c) The tumour sits where all the beams cross, so it receives every beam’s contribution — the full 50 Gy. Each patch of healthy tissue lies in the path of only one weak beam, so its dose is a small fraction of that. This is the same principle as part (b): the same energy spread through more tissue gives a smaller dose.

Question 6 The treated patient is a γ-ray source for a few days, so the standard protections apply. *Distance:* the radiation reaching another person falls off strongly with distance from the patient, so keeping space reduces their dose. *Time:* dose grows with exposure time, so short visits keep each person’s dose small. *Children and pregnant women:* children’s cells, and the cells of an unborn baby, divide rapidly and are therefore more sensitive to ionising radiation than an adult’s. *Fluids:* iodine the thyroid does not take up is passed out of the body in urine; drinking plenty of fluids removes this unused iodine sooner, shortening the time the patient remains radioactive.

Question 7 $t_{1/2} = 73.8$ days. (a) 147.6 days is $\frac{147.6}{73.8} = 2.0$ half-lives, so the fraction remaining is $\left(\frac{1}{2}\right)^2 = \frac{1}{4}$. (b) One-eighth remaining means $\left(\frac{1}{2}\right)^3$, i.e. 3 half-lives: $3 \times 73.8 = 221.4$ days.

Question 8 (a) Radiation is absorbed as it travels through matter (Section 3B). Close to the source the tissue receives the full output; a few centimetres away, much of the radiation has been absorbed or has spread out, so the dose is far smaller. Placing the source next to the tumour uses this steep fall-off: a very large dose at the tumour, a much smaller dose beyond it. (b) The iridium-192 stays inside a sealed capsule or wire: it irradiates the patient while it is there, but no radioactive material enters the patient’s tissues. Once the source is removed, nothing radioactive is left behind, so the patient is not a source of radiation to others.

Question 9 One-sixteenth remaining is $\left(\frac{1}{2}\right)^4$, so 4 half-lives must pass: $4 \times 6.6 = 26.4$ days.

Question 10 Fractionation uses the repair difference between healthy and diseased tissue. Each small fraction damages both tumour and healthy cells. Between fractions, healthy cells repair most of the damage; cancer cells repair poorly, so their damage builds up fraction after fraction until they die. One large dose would kill more healthy cells at once, before any repair could happen.

Question 11 $E = 0.80$ J. (a) Tumour: $m = 20\,\text{g} = 0.020\,\text{kg}$, so $D = \frac{E}{m} = \frac{0.80}{0.020} = 40$ Gy. (b) Healthy tissue: $D = \frac{0.80}{0.40} = 2.0$ Gy. (c) The tumour's dose is $\frac{40}{2.0} = 20$ times the healthy tissue's dose, even though the energies are equal. Dose is energy *per unit mass*: concentrating the same energy into a mass 20 times smaller raises the dose 20 times. Therapy is all about concentrating the energy in the diseased tissue.

Question 12 The thyroid gland needs iodine to make its hormones and actively collects iodine from the blood. Swallowed iodine-131 is therefore concentrated in thyroid tissue, where its β^- particles deliver their dose from within. A lung cancer does not collect iodine, so iodine-131 in the blood would not concentrate there; it would deliver no useful dose to the lung tumour and would only expose the rest of the body until it decayed or was passed out.

Question 13 $t_{1/2} = 11.4$ days. (a) 45.6 days is $\frac{45.6}{11.4} = 4.0$ half-lives, so the fraction remaining is $\left(\frac{1}{2}\right)^4 = \frac{1}{16}$. (b) Because radium behaves chemically like calcium, the body lays it down in bone — exactly where this patient's cancer is. The α particles it then emits travel only a few cells' thickness of tissue, so their dense ionisation is confined to the cancer cells immediately around each radium atom, with very little dose to the rest of the body. Targeting by chemistry, plus the short range of α radiation, concentrates the dose on the diseased tissue.

Question 14 A good evaluation hears the objection at full strength before answering it.

The case for the student's claim: it starts from a true claim. Ionising radiation damages DNA, and DNA damage that is mis-repaired can cause cancer — the long-term effect studied in Section 3E. Radiotherapy does give healthy tissue a scattered dose, and that dose does carry a small additional cancer risk years later. So the student is right that radiation can cause cancer, and right that treatment carries that risk.

The case against the claim: it ignores dose, control and purpose. The treatment delivers a large, planned, concentrated dose to a cancer that already exists and is life-threatening; the scattered dose to healthy tissue is far smaller, and the small long-term risk it brings is weighed against the immediate benefit of curing or controlling the existing disease. Without treatment, the existing cancer is by far the greater danger.

Conclusion: the claim identifies a real risk but is not a sound argument against treatment. Whether radiation "makes sense" is an evaluation of benefit against risk — and for a diagnosed cancer, the benefit of a controlled dose to the tumour outweighs the small risk of harm to healthy tissue.

Question 15 $t_{1/2} = 8.0$ days. (a) 32 days is $\frac{32}{8.0} = 4$ half-lives, so the fraction remaining is $\left(\frac{1}{2}\right)^4 = \frac{1}{16}$. (b) After four half-lives only one-sixteenth of the iodine-131 remains — and in reality less, because the body has also passed some out — so the radiation emitted by the patient is now a small fraction of its original value. The dose rates to people nearby are small in the same proportion, so the contact rules can be lifted after a few weeks. The decay is not permanent, but it is fast enough that the rules need not be either.

Question 16 The diagram should show a cross-section of the body with the tumour marked inside it, and at least four beams entering from different directions (for example left, right, and two angled beams), all crossing at the tumour.

Each beam is weak. A patch of skin where one beam enters receives only that one beam's small dose, and the healthy tissue along each beam's path receives only that beam's contribution. The tumour, however, sits where every beam arrives, so it receives the sum of all four doses. The total dose is therefore large at the tumour and small at every point along any single path — the geometry concentrates the dose at the crossing point. (Rotating the source continuously around the patient is the same idea taken further: every direction is weak, only the tumour gets the full sum.)

Question 17 $m = 70\,\text{kg}$, $D = 0.020$ Gy. (a) $E = Dm = 0.020 \times 70 = 1.4\,\text{J}$. (b) The energies are similar, but dose is energy per unit mass. The worker's 1.4 J is spread through 70 kg — a dose of only 0.020 Gy, far too dilute to kill cells in any number. The tumour's 1.5 J is packed into 0.025 kg — 60 Gy, enough ionisation to destroy the cells it passes through. The biological effect is set by the concentration of the energy, which is what the dose measures.

Question 18 *Outside the body:* α particles are stopped by a few centimetres of air or by the dead outer layer of the skin. From a source outside the body they never reach living cells, so they deposit no dose in tissue that matters. *Inside* *the body:* there is no dead protective layer between the source and living cells. The α particle's short range then means all of its ionisation is dumped densely into the living cells immediately next to the source, which is why internal α contamination is so damaging (Section 3E). *In therapy:* radium-223 turns this hazard into the treatment. Laid down in bone like calcium, each radium atom sits beside the cancer it is meant to kill; its α particles then irradiate exactly those neighbouring cancer cells and almost nothing else. The danger of internal α radiation becomes the precision of the therapy.

Question 19 (a) Iodine-131: 32 days is $\frac{32}{8.0}=4$ half-lives, so the fraction remaining is $\left(\frac{1}{2}\right)^4=\frac{1}{16}$ and the fraction decayed is $1-\frac{1}{16}=\frac{15}{16}$. Cobalt-60: 5.27 years is about 1925 days, so 32 days is only about $\frac{1}{60}$ of one half-life. The whole-half-life model says only that far less than half has decayed; in fact only about 1% has decayed, so nearly all the cobalt-60 remains. (b) The iodine-131 source delivers nearly all of its radiation in about a month; the cobalt-60 source delivers its radiation slowly over many years. For a treatment that must be finished in weeks — a swallowed or injected therapy — the short-lived isotope is right. For a machine used daily for years, a source whose output barely changes is right. Matching the half-life to the job is part of choosing the isotope.

Question 20 A strong evaluation covers suitability, benefit and risk.

Suitability: iodine-131 is suited to thyroid cancer for three physical reasons. (1) Targeting: the thyroid collects iodine from the blood to make hormones, so swallowed iodine-131 concentrates itself in thyroid tissue — including any thyroid cancer cells left after surgery — and the body does the delivering. (2) Radiation type: its β^- particles travel only a few millimetres, so the dose is deposited almost entirely in the tissue that absorbed the iodine, with little dose elsewhere. (3) Half-life: 8.0 days is long enough for uptake and dose delivery, short enough that the patient's radioactivity is almost gone within weeks.

Effect on damaged tissue: the β^- dose breaks the cancer cells' DNA faster than they can repair it; the cells stop dividing and die, and remaining cancer is destroyed or controlled.

Effect on healthy tissue: the dose to healthy tissue is small but not zero — some iodine circulates elsewhere before being passed out, and nearby tissue receives some β^- dose and some γ dose; the patient is briefly radioactive to others. The long-term risk of a radiation-induced second cancer exists but is small compared with the benefit of treating the existing cancer.

Conclusion: iodine-131 is a well-matched therapy: its chemistry targets the diseased tissue, its radiation confines the dose to that tissue, and its half-life limits the period of risk. Its use is justified because the benefit — destroying cancer that could otherwise be fatal — outweighs the limited, short-lived harm to healthy tissue.