Unit 12

Answers: Radioactivity

Quick checks

1 c Radioactivity comes from the nucleus. Heat, pressure and chemical reactions change only how atoms move and how their electrons are shared, so they make no difference to how fast the nuclei break down.

2 c The alpha particle takes away 2 protons ($Z - 2$); each beta particle adds one ($Z + 1 + 1$). Overall, Z is unchanged, so it is the same element again, but its mass number is 4 smaller: an **isotope** of the parent.

3 a Alpha particles are heavy, slow and carry a charge of +2, so they knock electrons off almost every atom they pass. That is also why they penetrate least: making so many ions uses up their energy quickly.

4 b The count must change when the thickness changes. Alpha particles would be stopped completely by even the thinnest foil, and gamma rays would pass through 0.1 mm of aluminium almost unchanged. A thin sheet absorbs part of the beta particles, more as it gets thicker, so beta is right.

5 a Inside the body nothing shields the cells. An alpha particle's strong ionizing power puts all its energy into a tiny region, badly damaging the cells there. A gamma ray, ionizing weakly, mostly passes out of the body. (Outside the body the order is the other way round: alpha is stopped by dead skin, gamma is the most dangerous.)

1 a. **b** An alpha particle is 2 protons and 2 neutrons, which is the nucleus of a helium-4 atom, $^{4}_{2}$.

1 b. **c** In beta decay a neutron turns into a proton (which stays) and an electron (which leaves). One more proton raises the atomic number by 1; the total of protons and neutrons, the mass number, is unchanged.

1 c. **b** Beta particles are negatively charged electrons, so they are attracted to the positive plate. Alpha particles, being positive, bend towards the negative plate; gamma rays go straight.

1 d. **a** Smoke detectors use americium-241, an alpha source: its alpha particles ionize the air between two plates strongly, and they are stopped by the air and the plastic case, so the detector is safe.

1 e. **c** The dose, which combines the energy left in the body with the kind of radiation, is measured in sieverts (Sv), usually in millisieverts or microsieverts. (The becquerel and the curie measure how many nuclei in a source decay each second, not the dose received.)

2 a. Each time a particle ionizes an atom, it uses up a little of its energy. Alpha particles, being heavy, slow and doubly charged, ionize almost every atom they pass, tens of thousands in each centimeter of air. So they use up all their energy within a few centimeters of air, or inside a sheet of paper, and stop. The stronger the ionizing power, the less the penetrating power.

2 b. An alpha particle has twice the charge of a beta particle, so the magnetic force on it is larger, but it is about 7,300 times heavier, and a heavy particle is much harder to turn. In a field that bends beta particles into tight curves, alpha particles curve only very slightly, and in the opposite direction, because their charge is positive.

2 c. The rays must pass through the skin and the healthy tissue to reach the tumor. Alpha particles are stopped by the dead outer layer of the skin, so they could never reach it. Gamma rays penetrate the body easily and can be aimed at the tumor from many directions, so the tumor gets a large dose while each part of the healthy tissue gets only a small one.

3 i.

Alpha particles	Beta particles
Helium nuclei: 2 protons + 2 neutrons.	Fast electrons, made when a neutron in the nucleus turns into a proton.
Charge +2.	Charge −1.
Mass about 4 u.	Mass about 1/1836 u.
Speed about 5% of the speed of light.	Speed up to 99% of the speed of light.
Least penetrating: stopped by paper or a few cm of air.	More penetrating: stopped by a few mm of aluminium.
Most strongly ionizing.	Less strongly ionizing.
Bend towards the negative plate, and only slightly in a magnetic field.	Bend towards the positive plate, and strongly in a magnetic field.
The nucleus's Z goes down by 2 and A by 4.	The nucleus's Z goes up by 1; A is unchanged.

3 ii.

Beta particles	Gamma rays
Particles of matter: fast electrons.	Electromagnetic waves.
Charge −1.	No charge.
Have a tiny mass, about 1/1836 u.	No mass.
Up to 99% of the speed of light.	Exactly the speed of light, 3×10^8 m/s.
Stopped by a few mm of aluminium.	Only reduced, by thick lead or concrete.
Ionize more strongly.	Ionize least.
Bent by electric and magnetic fields.	Not bent by any field.
Change the element (Z goes up by 1).	Don't change the nucleus's Z or A.

3 iii.

Penetrating power	Ionizing power
How far a radiation can travel through matter before it is stopped.	How many atoms a radiation ionizes along each centimeter of its path.
Greatest for gamma, least for alpha.	Greatest for alpha, least for gamma.
Decides which shield is needed (paper, aluminium, lead).	Decides how much harm it does to the cells it reaches.

4 a. **Radioactivity** is the breaking down of unstable atomic nuclei by themselves, giving out nuclear radiation (alpha particles, beta particles or gamma rays).
Features (any two):

- It happens by itself; nothing starts or stops it.
- It is not changed by heat, pressure or chemical combination, because it happens in the nucleus.
- When a charged particle is given out, the element changes into another element.
- It gives out energy, as the speed of the particles and as gamma rays.

4 b.

i. $^{238}_{92} \longrightarrow {}^{234}_{90} + {}^{4}_{2}$ $(238 = 234 + 4;\ 92 = 90 + 2)$

ii. $^{131}_{53} \longrightarrow {}^{131}_{54} + {}^{0}_{-1}$ $(131 = 131 + 0;\ 53 = 54 - 1)$

4 c. A radioactive source giving out all three radiations is placed in a lead block with a narrow channel, so that a thin beam comes out. The beam passes between two metal plates, one charged positive and one negative, in a vacuum (so the alpha particles are not stopped by air), and falls on a photographic plate or screen beyond.

- One beam bends towards the **negative** plate: it must be **positive**, the alpha particles.
- One beam bends towards the **positive** plate, and spreads out: it must be **negative**, the beta particles.
- One beam goes straight on: it has **no charge**, the gamma rays.

(Diagram: the lead block with the source and channel; the + plate and − plate; the beta beam curving towards +, the alpha beam curving less towards −, the gamma beam straight; the screen, as in Figure 12.2.) A magnetic field across the beam shows the same: alpha and beta bend opposite ways, gamma not at all.

4 d. **Alpha:** smoke detectors (americium-241: it ionizes the air strongly, and is stopped by the air and the case, so it is safe); static eliminators that ionize the air to remove static charge in factories (strong ionizing, short range).

Beta: thickness gauges for paper, plastic or foil (a thin sheet absorbs part of it, so the count shows the thickness); treating an overactive thyroid with iodine-131 (its short range in the body acts only inside the gland); carbon dating (the decay of carbon-14 is a clock).

Gamma: radiotherapy with cobalt-60 (penetrates the body to reach a deep tumor); sterilizing syringes and food in their packets (passes through the packaging); checking welds in steel (passes through thick metal); gamma camera scans with technetium-99m (gets out of the body to the camera).

(Any two for each.)

4 e. Nuclear radiation ionizes the atoms in the body's cells and damages their molecules, especially DNA. The cell may die, or survive with changed DNA.

- **Short-term effects** of a large dose (over about 1 Sv): radiation sickness (vomiting, weakness, fewer white blood cells and so infections, hair loss), burns of the skin; very large doses (about 4 Sv and more) can kill within weeks.
- **Long-term effects**, years later: cancers such as leukemia and thyroid, lung and bone cancer, and cataracts; the chance grows with the dose.
- Changes in the DNA of sex cells might be passed on to children (seen in animals; assumed possible in people).

Alpha emitters are most dangerous inside the body, gamma rays outside it.

4 f. **Handling:**

- Keep the **time** near a source as short as possible.
- Keep the **distance** large: use long tongs or remote handling, never bare hands; the gamma dose falls with the square of the distance.
- Use **shielding**: work behind lead bricks, lead glass or concrete walls.
- Wear gloves, a lab coat and a dosimeter badge; never eat or drink where sources are used; wash and check hands afterwards.

Storing:

- Keep sources in thick lead (or concrete) containers in a locked place, away from people.
- Label every container with the radiation warning sign and what is inside.
- Record every source, where it is and who is responsible, so none is ever lost or thrown away.
- Store radioactive waste shielded until it has decayed; seal long-lived waste in steel and concrete for very long storage; follow the license conditions of the country's regulatory body.

4 g. Lead doesn't stop gamma rays; it **reduces** them, cutting them to half for every 1.2 cm or so (for cobalt-60). One centimeter of lead lets through a little more than half of them ($0.5^{1/1.2} \approx 0.56$, about 56%), so the apron would only roughly halve the dose. To cut a strong source's gamma rays to a safe level needs many centimeters of lead or a meter or more of concrete, together with distance and short times.

5 a. $A = 32$, $Z = 15 + 1 = 16$: **sulphur-32**.

$$^{32}_{15} \longrightarrow {}^{32}_{16} + {}^{0}_{-1}$$

5 b. The mass number falls by $237 - 209 = 28$, so there are $28 \div 4 = \mathbf{7}$ **alpha particles**. They lower the atomic number by $7 \times 2 = 14$, to $93 - 14 = 79$. Bismuth is 83, so it must rise by $83 - 79 = 4$: **4 beta particles**.
Check: $209 + 28 = 237$; $83 + 14 - 4 = 93$. ✓

5 c. New dose rate $= 36 \div 3^2 = 36 \div 9 = 4\ \mu$ per hour.
Dose in 2 hours $= 4 \times 2 = 8\ \mu$.
4 μSv per hour; 8 μSv in 2 hours (instead of 72 μSv had she stayed at 1 m).

5 d. Yearly dose $= 2 \times 8 \times 250 = 4{,}000\ \mu = 4$.
4 mSv a year, a fifth of the 20 mSv limit, and less than twice the natural background of about 2.4 mSv a year that everyone receives anyway.