Unit 12

Radioactivity

This unit online, with its interactives:
science-playground.com/s/9a12

In the radiotherapy room of a cancer hospital, a patient lies very still on a table while a heavy machine turns slowly around them. Inside its head is a small metal cylinder of **cobalt-60**, a few centimeters long. It has no battery and no plug, yet day and night, for years, it sends out invisible rays strong enough to destroy a tumor deep inside the body. When the machine is "off", the cobalt is not switched off at all: it is simply rolled back inside a thick shield of heavy metal, because nothing can stop it from giving out its rays.

The cobalt-60 is **radioactive**: the nuclei of its atoms are unstable, and each one, sooner or later, breaks down by itself and throws out radiation. This unit is about that radiation: the three kinds that come out of nuclei, how they differ, what we use them for, how they can harm us, and how people who work with them keep themselves and everyone else safe.

12.1 Introduction of nuclear radiation

Every atom has a tiny **nucleus** of protons and neutrons, held together by the strong nuclear force, with electrons around it. In most atoms around you, in the oxygen you breathe and the iron in a bicycle, the nucleus is **stable**: it will stay exactly as it is forever. But some nuclei have too many neutrons, too few, or are simply too big, and they are **unstable**. An unstable nucleus sooner or later changes into a more stable one by throwing out a particle or a burst of energy.

Radioactivity is the breaking down of unstable nuclei by themselves, giving out radiation. The radiation that comes out is called **nuclear radiation** (or radioactive radiation), because it comes from the nucleus. A substance whose nuclei do this is a **radioactive substance**, and an isotope with unstable nuclei is a **radioisotope**: uranium-238, radium-226, carbon-14 and cobalt-60 are examples. The nucleus that is left after the change is called the **daughter nucleus**, and the one that broke down the **parent**.

Radioactivity has three features that set it apart from everything in chemistry:

- **It happens by itself.** Nothing has to start it, and nothing can stop it.

- **Nothing outside the nucleus changes it.** Heating a radioactive substance, cooling it, squeezing it, or combining it into a compound makes no difference to how fast it gives out radiation. Chemical reactions only move electrons around; the nucleus doesn't notice.
- **The element changes.** When a nucleus throws out a charged particle, its number of protons changes, so it becomes a different element. Dalton thought atoms of one element could never turn into another; radioactivity shows that they can.

Some radioactive substances are found in nature, such as uranium and thorium in rocks, radon gas seeping out of the ground, and potassium-40 in every banana and in your own body. This is **natural radioactivity**. Others are made by people, in nuclear reactors or particle accelerators, such as cobalt-60 and technetium-99m for hospitals and americium-241 for smoke detectors: **artificial radioactivity**.

A STORY FROM SCIENCE

Three kinds of rays, named in order

After Henri Becquerel found in 1896 that uranium gives out rays by itself, the young New Zealander **Ernest Rutherford** set out to find what the rays were. In a paper published in 1899 he described covering uranium with thin sheets of aluminium foil, one after another, and measured how much radiation still came through. The first few sheets cut it down sharply; after that, more sheets made hardly any difference. So there had to be at least two kinds: one stopped by a very thin layer, which he called **alpha** (α), and a far more penetrating kind, **beta** (β), after the first two letters of the Greek alphabet. In 1900 the French chemist **Paul Villard** found a third kind from radium that passed through layers of metal that stopped the beta rays, and bent not at all in a magnet. Rutherford named it **gamma** (γ) in 1903, the third letter. The names stuck, even though alpha and beta turned out to be particles, not rays.

Check 1

A sample of radium is heated strongly in a flame and then mixed into a compound. What happens to the rate at which it gives out radiation?

a it increases when it is heated
b it stops once the radium is in a compound
c it doesn't change
d it decreases when it is heated

f. Describe the methods of safely handling and storing radioactive materials.

g. **Think:** A student says, "Lead stops gamma rays, so a 1 cm lead apron makes a gamma source completely safe." What is wrong with this, and what does 1 cm of lead really do to cobalt-60's gamma rays?

5. Numerical problems

a. Phosphorus-32 ($Z = 15$) gives out a beta particle. What does it become? (Element 16 is sulphur, S.)

b. Neptunium-237 ($Z = 93$) decays through a chain of alpha and beta decays to bismuth-209 ($Z = 83$). How many alpha and how many beta particles are given out?

c. A radiographer stands 1 m from a gamma source, where the dose rate is 36 μSv per hour. She steps back to 3 m. Find the new dose rate, and the dose she receives in 2 hours there.

d. A worker in a hospital's nuclear medicine department receives 2 μSv per hour on average at work. She works 8 hours a day for 250 days a year. Find her yearly dose in millisieverts, and compare it with the limit of 20 mSv a year for radiation workers.

Found a mistake? Please tell us.

Types of nuclear radiations

Unstable nuclei give out three kinds of radiation: **alpha** (α), **beta** (β) and **gamma** (γ). A nucleus is written ${}^{A}_{Z}\mathrm{X}$: X is the element's symbol, Z its **atomic number** (the number of protons) and A its **mass number** (protons + neutrons), as in Unit 6. Carbon-14, with 6 protons and 8 neutrons, is ${}^{14}_{6}\mathrm{C}$.

Alpha (α) radiation

An **alpha particle** is a cluster of **2 protons and 2 neutrons**, stuck tightly together. That is exactly the nucleus of a helium atom, so an alpha particle is written ${}^{4}_{2}\mathrm{He}$ or ${}^{4}_{2}\alpha$. Its charge is +2 (two protons, no electrons) and its mass number 4. Alpha particles come mostly from very heavy nuclei, such as uranium, radium and polonium, which are too big to be stable.

When a nucleus gives out an alpha particle, it loses 2 protons and 2 neutrons, so:

- its **atomic number goes down by 2** (it becomes the element two places earlier in the periodic table);
- its **mass number goes down by 4**.

Radium-226 (88 protons) gives out an alpha particle and becomes radon, with mass number $226 - 4 = 222$ and $88 - 2 = 86$ protons:

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

Check both sides: the mass numbers add up the same ($226 = 222 + 4$), and so do the atomic numbers ($88 = 86 + 2$). Every nuclear equation balances like this.

Beta (β) radiation

A **beta particle** is a fast **electron**, with a charge of -1 and almost no mass. It is written ${}^{0}_{-1}\mathrm{e}$ or ${}^{0}_{-1}\beta$: mass number 0, because an electron's mass is less than a two-thousandth of a proton's, and "atomic number" -1 for its charge.

But a nucleus has no electrons in it. Where does the beta particle come from? In a nucleus with too many neutrons, **one neutron turns into a proton and an electron**. The proton stays in the nucleus; the electron is made at that moment and shot out at very high speed. (A tiny, almost massless particle with no charge, an **antineutrino**, flies out with it, and shares the energy.) So when a nucleus gives out a beta particle:

- its **atomic number goes up by 1** (one more proton: the next element in the periodic table);
- its **mass number stays the same** (one neutron fewer, one proton more).

Carbon-14 (6 protons, 8 neutrons) gives out a beta particle and becomes nitrogen-14 (7 protons, 7 neutrons):

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

Mass numbers: $14 = 14 + 0$. Atomic numbers: $6 = 7 + (-1)$. Both balance.

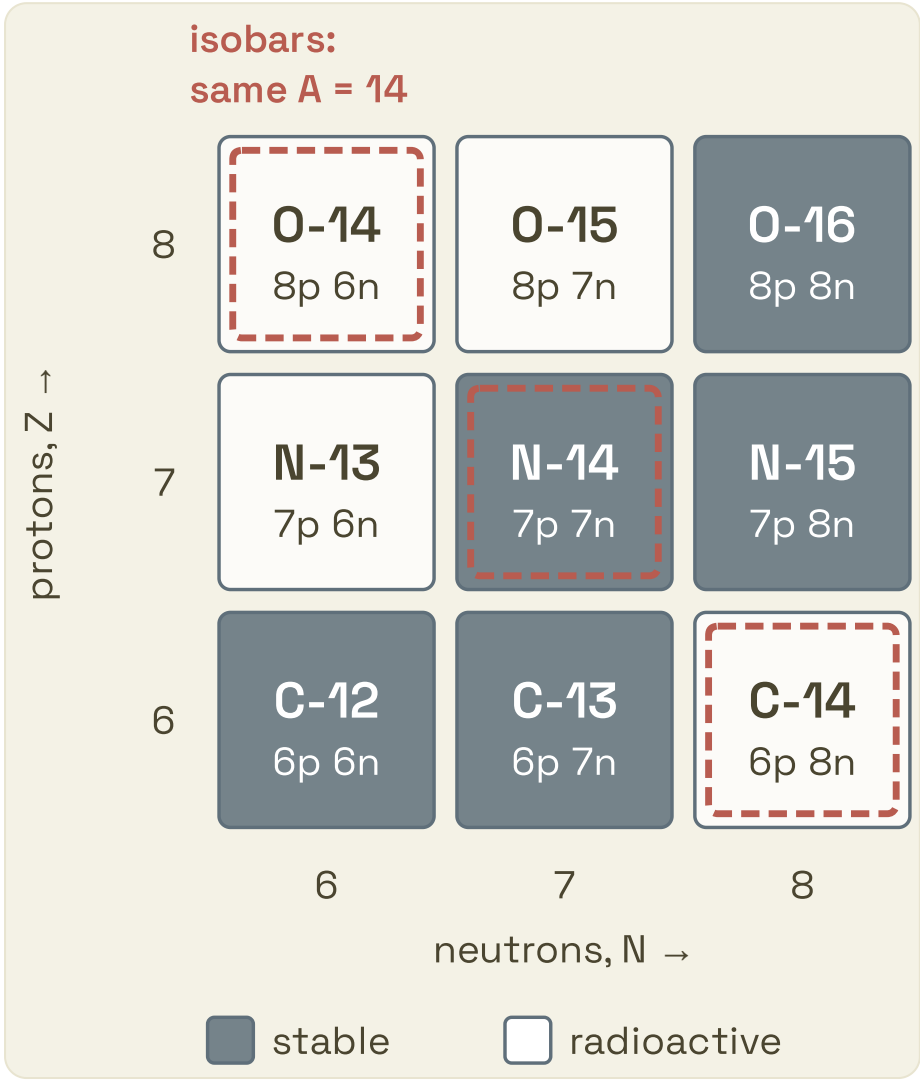


Figure 12.1 *A patch of the chart of nuclei, protons up and neutrons across. In beta decay, carbon-14 (bottom right) moves one step up and to the left, along its dashed diagonal of* ***isobars****, to nitrogen-14 in the middle: one neutron fewer, one proton more, the same mass number 14. Nitrogen-14 is stable (shaded), so the change stops there.*

b. When a nucleus gives out a beta particle, its:

- **a** mass number goes down by 1
- **b** atomic number goes down by 1
- **c** atomic number goes up by 1 and its mass number stays the same
- **d** atomic number and mass number both stay the same

c. Between two oppositely charged plates, beta particles bend:

- **a** towards the negative plate
- **b** towards the positive plate
- **c** neither way
- **d** first one way, then the other

d. The source in a household smoke detector gives out:

- **a** alpha particles
- **b** beta particles
- **c** gamma rays
- **d** X-rays

e. The SI unit used for the dose of radiation a person receives is the:

- **a** becquerel
- **b** joule
- **c** sievert
- **d** curie

2. Give reasons

a. Alpha particles have the least penetrating power, though they have the greatest ionizing power.

b. In a magnetic field, an alpha beam bends much less than a beta beam.

c. Gamma rays, not alpha particles, are used to treat a tumor deep inside the body.

3. Differentiate between

i. Alpha particles and beta particles

ii. Beta particles and gamma rays

iii. Penetrating power and ionizing power

4. Answer the following questions

a. What is radioactivity? Write two of its features.

b. Write the equations for (i) the alpha decay of uranium-238 ($Z = 92$; element 90 is thorium, Th) and (ii) the beta decay of iodine-131 ($Z = 53$; element 54 is xenon, Xe).

c. How can you show by experiment that alpha particles are positive, beta particles negative and gamma rays uncharged? Draw a labeled diagram.

d. Write two uses each of alpha, beta and gamma radiation, giving the reason in each case.

e. What are the health hazards of nuclear radiation?

IN SHORT

- **Radioactivity** is the breaking down of unstable nuclei by themselves, giving out **nuclear radiation**. Heat, pressure and chemical reactions don't change it, and the element changes.
- **Alpha** (^4_2He): 2 protons + 2 neutrons; charge +2, mass about 4 u; Z goes down by 2, A by 4.
- **Beta** ($^0_{-1}\text{e}$): a fast electron made when a neutron turns into a proton; charge −1, mass about 1/1836 u; Z goes up by 1, A stays the same.
- **Gamma** (γ): an electromagnetic wave; no charge, no mass; Z and A stay the same.
- In nuclear equations, the mass numbers and the atomic numbers each add up to the same total on both sides.
- **Penetrating power:** alpha least (stopped by paper), beta more (a few mm of aluminium), gamma most (only reduced by thick lead or concrete). **Ionizing power** is in the opposite order: alpha most, gamma least.
- In electric and magnetic fields, alpha and beta bend in opposite directions (alpha far less in a magnet), gamma not at all.
- **Uses:** radiotherapy, gamma camera scans, thyroid treatment, sterilizing, thickness gauges, checking welds, leak tracing, smoke detectors, food keeping, pest control, crop breeding, dating.
- **Hazards:** ionization damages DNA: radiation sickness and burns after large doses, cancer later; dose in **sieverts**. Outside the body gamma is most dangerous, inside it alpha.
- **Safety:** time, distance (gamma falls with distance squared) and shielding; tongs, dosimeters, no eating; sources locked in labeled lead containers, recorded, and waste stored until harmless, under license.

Exercise

1. Choose the correct option

a. An alpha particle is the same as:

a a hydrogen nucleus
b a helium nucleus
c an electron
d a neutron

CAREFUL

The beta electron is not one of the atom's electrons

A beta particle comes out of the **nucleus**, made when a neutron changes into a proton. It is not knocked off from the electrons around the nucleus. That is why beta decay changes the element (the number of protons changes), while losing an outer electron only makes an ion of the same element.

Gamma (γ) radiation

Gamma rays are not particles of matter at all. They are **electromagnetic waves**, like light, radio waves and X-rays, but with far more energy and a far shorter wavelength (usually shorter than about a hundredth of a nanometer). They have **no charge and no mass**, and they travel at the speed of light, 3×10^8 m/s.

A nucleus often has some energy left over after it has given out an alpha or beta particle: it is **excited**, like a ball resting on a shelf instead of on the floor. It settles down by giving out that extra energy as a gamma ray. Nothing in the nucleus changes but its energy, so **neither the atomic number nor the mass number changes**. Cobalt-60, for example, gives out a beta particle and becomes nickel-60, which is left excited (marked with a star) and at once gives out gamma rays:

$$^{60}_{27}\text{Co} \longrightarrow {}^{60}_{28}\text{Ni}^* + {}^{0}_{-1}\text{e} \qquad {}^{60}_{28}\text{Ni}^* \longrightarrow {}^{60}_{28}\text{Ni} + \gamma$$

It is these gamma rays, not the beta particles (which are stopped inside the cobalt's steel capsule), that a cobalt machine aims at a tumor.

Radiation	What leaves the nucleus	Atomic number, Z	Mass number, A
alpha, ^4_2He	2 protons + 2 neutrons	goes down by 2	goes down by 4
beta, $^0_{-1}\text{e}$	an electron (a neutron became a proton)	goes up by 1	stays the same
gamma, γ	energy only	stays the same	stays the same

Writing nuclear equations

To complete a nuclear equation, use two rules: **the mass numbers on the two sides add up to the same total, and so do the atomic numbers.** Find the missing A and Z first, then look up the element whose atomic number is Z.

WORKED EXAMPLE

Polonium gives out an alpha particle

Polonium-210 ($Z = 84$) gives out an alpha particle. Write the equation and name the daughter nucleus. (Element 82 is lead, Pb.)

Answer

$$^{210}_{84}\text{Po} \longrightarrow {}^{A}_{Z}\text{X} + {}^{4}_{2}\text{He}$$

Mass numbers: $210 = A + 4$, so $A = 206$. Atomic numbers: $84 = Z + 2$, so $Z = 82$, which is lead.

$$^{210}_{84}\text{Po} \longrightarrow {}^{206}_{82}\text{Pb} + {}^{4}_{2}\text{He}$$

The daughter is lead-206, a stable nucleus.

WORKED EXAMPLE

Strontium gives out a beta particle

Strontium-90 ($Z = 38$), found in the fallout of nuclear bomb tests, gives out a beta particle. What does it become? (Element 39 is yttrium, Y.)

Answer

$$^{90}_{38}\text{Sr} \longrightarrow {}^{A}_{Z}\text{X} + {}^{0}_{-1}\text{e}$$

Mass numbers: $90 = A + 0$, so $A = 90$. Atomic numbers: $38 = Z - 1$, so $Z = 39$: yttrium.
It becomes yttrium-90, $^{90}_{39}\text{Y}$. (Yttrium-90 is itself radioactive and gives out another beta particle to become zirconium-90, which is stable.)

Characteristics of alpha, beta and gamma radiations

The three radiations differ in four ways that matter: their **charge**, their **mass**, how far they **penetrate** (pass through) matter, and how strongly they **ionize** it.

Charge

Alpha particles have a charge of **+2** (the charge of two protons, $2 \times 1.6 \times 10^{-19}$ C), beta particles **−1** (the charge of an electron, -1.6×10^{-19} C), and gamma rays **none**.

The way to show this is to send the radiation through an electric or a magnetic field. A charged particle moving across a field is pushed sideways; an uncharged one goes straight on.

- **Between two charged plates**, alpha particles bend towards the negative plate (opposites attract), beta particles towards the positive plate, and gamma rays pass

Nuclear Materials Management Division of the Ministry of Education, Science and Technology).

CAREFUL

Being near radiation doesn't make you radioactive

A person who has had an X-ray or radiotherapy, food that has been sterilized with gamma rays, or a syringe sterilized in its packet does **not** become radioactive. Radiation passing through something leaves it as it was, except for the damage it does on the way. Something becomes dangerous to others only if radioactive **material** gets onto it or into it: that is **contamination**, and it is why sources are sealed and hands are washed.

A STORY FROM SCIENCE

The lost source of Goiânia

In 1985 a private radiotherapy clinic in Goiânia, Brazil, moved to new premises and left an old radiotherapy machine behind in its abandoned building. Inside the machine's head was a capsule of **cesium-137**, a powder that glowed blue in the dark. In September 1987 two men took the machine apart for scrap and broke the capsule open. Fascinated by the glow, people passed the powder around, rubbed it on their skin and took it home. Within weeks, four people had died of radiation sickness, including a six-year-old girl, and 249 people were found to be contaminated. More than 100,000 people had to be checked with detectors, and whole houses were demolished and buried as radioactive waste. Every rule in the list above, labeling, locking, keeping records, never letting a source go missing, was broken in Goiânia.

WORKED EXAMPLE

How much lead?

Each 1.2 cm of lead cuts the gamma rays from cobalt-60 to half. What fraction of the gamma rays gets through 4.8 cm of lead?

Answer

4.8 cm is $4.8 \div 1.2 = 4$ layers of 1.2 cm. Each layer lets through half of what reaches it:

$$\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{16}$$

One sixteenth gets through, about 6%. Notice that lead never brings it to zero: another 1.2 cm only halves it again, to 1/32.

- Never eat, drink or put on make-up where radioactive materials are used; wash hands carefully afterwards, and check them with a detector.
- Work behind **shields**: lead bricks, lead-glass windows, or thick concrete walls for strong gamma sources.
- Keep the time near a source short and the distance as large as possible.
- In a school laboratory, sources are small, sealed and kept by the teacher; students watch from a distance and never handle them.

Storing radioactive materials safely

- Keep sources in **thick lead containers** (or concrete, for strong ones), in a locked room or safe, away from where people sit or work.
- Label every container with the **radiation warning sign**, the black or magenta trefoil on yellow ☢, with what is inside and when.
- Keep a written record of every source: where it is, who has it, how strong it is. A source must never get lost, sold as scrap or thrown away with ordinary rubbish.
- **Radioactive waste** is stored until it is harmless. Many sources lose their activity quickly: technetium-99m halves every 6 hours, so after two days only 1/256 of it is left, and its waste is simply kept shielded until then. Long-lived waste, such as used fuel from nuclear power stations, stays dangerous for thousands of years; it is sealed in steel and concrete, and some countries are building stores for it deep underground in stable rock.
- In Nepal, the Radioactive Substances (Use and Regulation) Act, in force since July 2020 (2077 BS), says that no one may work with nuclear or radioactive materials without a license, and provides for a regulatory body to grant them. Until that body is set up, government offices share the work (as of 2026, among them the

WORKED EXAMPLE

How many alphas and betas?

Uranium-238 ($Z = 92$) breaks down in a long chain of steps, giving out only alpha and beta particles, until it becomes stable lead-206 ($Z = 82$). How many alpha particles and how many beta particles does each uranium nucleus give out on the way?

Answer

Only alpha particles change the mass number, by 4 each. The mass number falls from 238 to 206, by 32, so the number of alpha particles is $32 \div 4 = \mathbf{8}$.
Eight alpha particles alone would lower the atomic number by $8 \times 2 = 16$, from 92 to 76. But lead is 82, so the atomic number must go back **up** by $82 - 76 = 6$.
Each beta particle raises it by 1, so there are **6** beta particles.
Check: ${}^{238}_{92}\mathrm{U} \longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\,{}^{4}_{2}\mathrm{He} + 6\,{}^{0}_{-1}\mathrm{e}$. Mass numbers: $206 + 32 + 0 = 238$.
Atomic numbers: $82 + 16 - 6 = 92$. ✓
8 alpha particles and 6 beta particles.

Check 2

A nucleus gives out one alpha particle and then two beta particles. What happens overall to its atomic number?

a it goes down by 4
b it goes down by 2
c it stays the same
d it goes up by 2

DID YOU KNOW?

Uranium in your own district

Uranium-238 takes 4.5 billion years for half of it to decay, about the age of the Earth, so half the uranium the Earth was born with is still here, in granite, in soil and in the rocks of the Himalaya. On its way to lead it passes through radium and **radon**, a radioactive gas, which seeps out of the ground everywhere. It gathers in closed rooms, especially basements, and breathing it is, after smoking, the commonest cause of lung cancer in the world. Opening windows clears it. The whole chain, all 14 steps, is drawn in Going Further 9–12: From uranium to lead.

straight between them.

- **In a magnetic field**, alpha and beta particles curve in opposite directions, because their charges are opposite; gamma rays go straight.

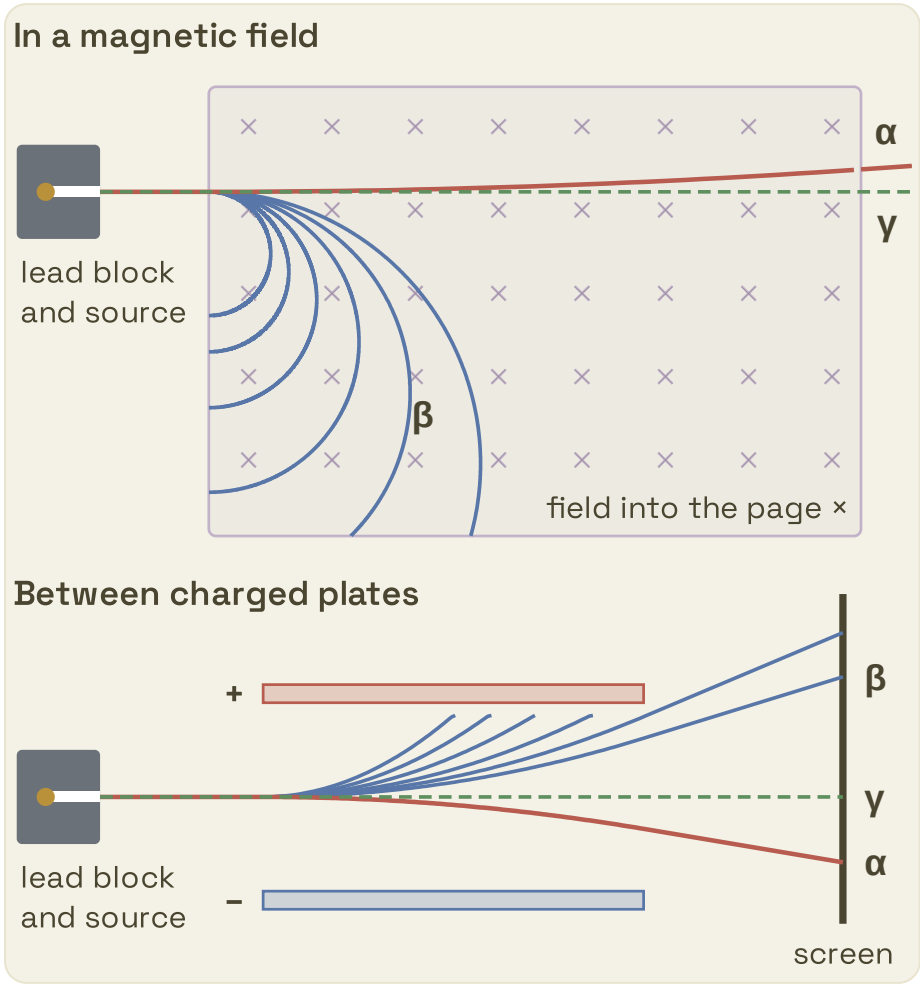


Figure 12.2 *The three radiations from a source in a lead block, in a vacuum, to scale. **Top:** in a magnetic field into the page (×), beta particles curve strongly downward, each in a circle whose size depends on its speed, so they spread into a fan; the alpha particles curve the other way, but so slightly that the beam looks almost straight; gamma rays go straight. **Bottom:** between charged plates, beta particles bend towards the + plate (the slowest hit it), alpha particles towards the – plate, gamma rays go straight. The paths are worked out for 5 MeV alpha particles and beta particles of 0.3 to 2.3 MeV.*

Look at Figure 12.2 closely. Two things in it may surprise you.

The beta particles spread out. All the alpha particles from one kind of nucleus come out at the same speed, so they form one sharp beam. Beta particles come out at every speed from almost zero up to a top speed, because each one shares its energy

Methods of safely handling and storing nuclear materials

People who work with radioactive materials (in hospitals, factories, laboratories and power stations) keep their doses low by three simple rules: **time, distance and shielding**.

Time. The dose is in proportion to the time spent near a source: half the time, half the dose. Work is planned so that it is done quickly, and nobody stays near a source longer than they must.

Distance. Alpha and beta particles are stopped by a little air. Gamma rays from a small source spread out in all directions, so their strength falls with the **square** of the distance: twice as far away, a quarter of the dose; three times as far, a ninth. Sources are never touched by hand, but picked up with long **tongs** or handled by remote control.

Shielding. A barrier between the source and the person absorbs the radiation: paper or the source's own case for alpha, a few millimeters of aluminium or plastic for beta, and thick lead or concrete for gamma. That is why the rooms where cobalt-60 machines work have concrete walls more than a meter thick.

WORKED EXAMPLE

Twice as far

A gamma source gives a dose rate of 40 µSv per hour at a distance of 1 m. What is the dose rate at 2 m and at 4 m? How long could a worker stay at 4 m before receiving 20 µSv?

Answer

The dose rate falls with the square of the distance.
At 2 m (twice as far): $40 \div 2^2 = 40 \div 4 = 10$ μSv per hour.
At 4 m (four times as far): $40 \div 4^2 = 40 \div 16 = 2.5$ μSv per hour.
Time to receive 20 µSv at 4 m: $20 \div 2.5 = 8$ hours.
10 µSv per hour at 2 m, 2.5 µSv per hour at 4 m, and 8 hours. At 1 m the same 20 µSv would come in only half an hour: distance protects very well.

Handling radioactive materials safely

- Handle sources only with **tongs**, gloves or remote-controlled arms, never with bare hands, and keep them pointed away from people.
- Wear a lab coat and gloves, and a **dosimeter** (a small badge that records the dose received), checked regularly.

atomic bombs of 1945, but the risk is assumed to exist, which is why the reproductive organs are shielded during X-rays.

CAREFUL

Outside the body and inside it

Which radiation is most dangerous depends on where the source is.

- **Outside the body**, gamma rays are the most dangerous: they pass through clothes and skin to every organ. Beta particles can burn the skin and eyes. Alpha particles are stopped by the dead outer layer of the skin and do no harm.
- **Inside the body** (breathed in, swallowed, or through a wound), alpha emitters are the most dangerous. All of an alpha particle's energy is dumped in a few cells right beside it, so the damage is concentrated where it is hardest to repair. Radon gas, breathed into the lungs, harms them this way.

A STORY FROM SCIENCE

The Radium Girls

In the 1910s and 1920s, hundreds of young women in factories in the United States painted watch faces with a glowing paint that contained radium, so the numbers could be read in the dark. To keep a fine point on their brushes, they were told to shape the tips with their lips. Each lick put a little radium into their bodies, and radium, which the body treats like calcium, settled in their bones, where its alpha particles kept destroying the tissue around it. Many of them suffered crumbling jaws, anemia and bone cancer, and dozens died. Some of the women took the factory owners to court, and their cases led to new rules protecting workers from radiation. The limits that protect the staff of every radiotherapy department today grew out of what happened to them.

Check 5

Which radiation is most dangerous when its source is **inside** the body?

a alpha, because it gives all its energy to the few cells around it

b gamma, because it penetrates most

c beta, because it is fastest

d none of them, because the skin protects us

with an antineutrino in a different way. Faster ones bend less and slower ones more, so the beta beam spreads into a fan.

The alpha beam hardly bends in the magnet. An alpha particle has twice the charge of a beta particle, but it is about 7,300 times heavier. A heavy particle is hard to turn: in a magnetic field strong enough to bend the beta particles into tight curves, the alpha particles' path curves about 35 to 150 times less (depending on the beta's speed). Rutherford needed a very strong magnet to bend alpha particles at all; he managed it in 1903, and the direction of the bend proved they are positive. Between charged plates the difference is smaller, so there the alpha beam does bend visibly, though still less than even the fastest beta particles.

CAREFUL

In the exam

Many books draw the alpha beam bending in a magnetic field almost as much as the beta beam, only the other way. Draw the **directions** correctly (alpha and beta opposite, gamma straight, alpha towards the negative plate between plates) and say that **alpha bends less than beta because it is much heavier**. That earns the marks, and it is the true picture.

Mass

An alpha particle's mass is 6.64×10^{-27} kg, about 4 u (4 times a proton's; 1 u, the atomic mass unit, is about 1.66×10^{-27} kg). A beta particle's is 9.11×10^{-31} kg, about $\frac{1}{1836}$ of a proton's, so an alpha particle is about 7,300 times heavier. Gamma rays have no mass.

Their **speeds** differ too. An alpha particle leaves its nucleus at about 1.5×10^{7} m/s, around 5% of the speed of light: fast, but slow next to the others. Beta particles come out at up to 99% of the speed of light, and gamma rays travel at the speed of light, 3×10^{8} m/s.

Penetrating power

The **penetrating power** of a radiation is how far it can travel through matter before it is stopped.

- **Alpha particles** have the **least** penetrating power. They travel only about 3 to 7 cm in air, and a sheet of paper, or the dead outer layer of your skin, stops them completely.
- **Beta particles** penetrate **more**: up to a few meters of air, and through paper, cloth and thin plastic. A few millimeters of aluminium stops them.

- **Gamma rays** penetrate **most**. They pass through paper, aluminium, the human body and walls, and even lead only **reduces** them: each 1.2 cm of lead (or about 6.6 cm of concrete) cuts the gamma rays of cobalt-60 to half. No thickness stops every last gamma ray, but enough lead or concrete makes them too few to matter.

Ionizing power

As alpha, beta and gamma radiation pass through air, they knock electrons off the atoms they meet, leaving the atoms as positive **ions**. This is **ionization**, and the **ionizing power** of a radiation is how many ions it makes along each centimeter of its path.

- **Alpha particles** ionize **most strongly**: tens of thousands of ion pairs in each centimeter of air. Big, slow and doubly charged, an alpha particle tugs hard on every electron it passes.
- **Beta particles** ionize **less**: about a hundred ion pairs a centimeter, very roughly. They are small, fast and singly charged.
- **Gamma rays** ionize **least**: having no charge, they only rarely hit an electron, making a few ions over a long path.

Notice that the order is exactly the opposite of penetrating power, and that is no accident. Every ion a particle makes costs it a little of its energy. An alpha particle, making so many ions, uses up all its energy in a few centimeters of air and stops. A gamma ray, making very few, keeps its energy and goes a long way. **The more strongly a radiation ionizes, the less it penetrates.**

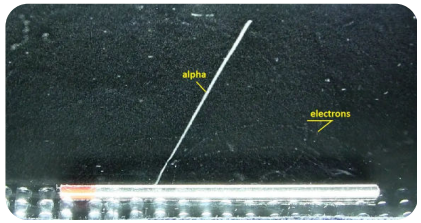


Figure 12.3 *Radiation from a thorium rod made visible in a cloud chamber, where each ion becomes the seed of a tiny droplet of mist. The bright, straight track is an alpha particle: it makes so many ions that its trail is a thick line of mist, and it ends after a few centimeters. The faint wisps to the right are electrons, which make far fewer ions along their way and are knocked about easily because they are so light.*

Photo: Cloudylabs, CC BY-SA 3.0

cell follows. A cell with damaged DNA may repair itself, may die, or may survive with its DNA changed, and then it may one day grow out of control as a cancer.

The dose. How much harm radiation does depends on the energy it leaves in the body and on the kind of radiation. Both are put together in one number, the **dose**, measured in **sieverts** (Sv). A sievert is a very large dose, so everyday doses are given in millisieverts (1 mSv = 0.001 Sv) or microsieverts (1 μSv = 0.001 mSv).

Dose	What it is
about 0.02 to 0.1 mSv	a chest X-ray (one view or two)
about 2.4 mSv a year	the world's average natural background radiation, from rocks, radon, space, food and our own bodies
about 8 mSv	a CT scan of the abdomen
1 mSv a year	the limit for the public from man-made sources (not counting medical care)
20 mSv a year (on average)	the limit for people who work with radiation
100 mSv	the lowest dose at which a rise in cancer has been seen
1,000 mSv (1 Sv) in a short time	radiation sickness
about 4,000 to 5,000 mSv (4 to 5 Sv) in a short time	kills about half of those who receive it, without medical treatment, within two months

The harm falls into two kinds.

- **Short-term effects**, after a large dose received in a short time, over about 1 Sv. **Radiation sickness**: vomiting, tiredness, a drop in white blood cells and so infections, hair falling out, and **burns** on the skin. Very large doses damage the bone marrow and the gut so badly that the person dies within weeks. Workers at the Chernobyl power station in 1986 suffered this.
- **Long-term effects**, which can follow even smaller doses, years later. **Cancer**, especially leukemia (cancer of the blood) and thyroid, lung and bone cancer. **Cataracts** in the eyes. The more the dose, the higher the chance; at the low doses of everyday life the extra chance is too small to measure, but it is assumed never to be quite zero, so doses are always kept as low as reasonably possible.

Radiation can also change the DNA in sperm and egg cells. Such a change, a **mutation**, could be passed to children. In animals given large doses this has been seen; in people it has not been clearly seen, even among the children of the survivors of the

In agriculture and food



Figure 12.5 *The americium-241 source from a smoke detector, smaller than a shirt button. It holds a fraction of a microgram of americium. Its alpha particles cannot get through the air and plastic around it, which is why the detector is safe, but the source must never be opened, swallowed or breathed in.*
Photo: MedicalReference, CC BY-SA 3.0

- **Keeping food longer.** Strong gamma rays kill the bacteria, molds and insects in grain, spices and fruit, and stop potatoes and onions sprouting. The food does **not** become radioactive, just as you don't become radioactive after an X-ray.
- **Controlling insect pests.** Male insects are raised in millions, made sterile with gamma rays and released; females that mate with them lay eggs that don't hatch, and the pest dies out over a few generations. This **sterile insect technique** drove the screwworm fly, a pest of cattle, out of the United States, Mexico and Central America for decades.
- **New crop varieties.** Seeds exposed to gamma rays get random changes in their DNA; plant breeders grow thousands of them and keep the rare plants that are better, with higher yields, shorter stems or resistance to disease. Thousands of crop varieties grown around the world, including rice, wheat and barley, were bred this way.

In finding ages

The carbon in every living thing contains a fixed small share of radioactive **carbon-14**. When the plant or animal dies, it takes in no more, and the carbon-14 it has slowly decays. Measuring how much is left tells how long ago it died, up to about 50,000 years: this is **carbon dating**, which you will meet in Grade 10 Optional Science. Rocks are dated the same way with uranium and lead, which is how we know the Earth is about 4.5 billion years old.

Check 4

A factory makes aluminium foil 0.1 mm thick and wants a gauge to keep it even. Which source should the gauge use?

a alpha, because it ionizes strongly
b beta, because a thin sheet absorbs part of it
c gamma, because it penetrates most
d any of the three works equally well

Health hazards of nuclear radiations

The very thing that makes nuclear radiation useful, its power to ionize, is what makes it dangerous. When radiation passes through the body, it ionizes the atoms in the cells. That can break the molecules of a cell, above all its **DNA**, the instructions the

The three compared

Property	Alpha (α)	Beta (β)	Gamma (γ)
What it is	helium nucleus, 2 protons + 2 neutrons	fast electron from the nucleus	electromagnetic wave
Symbol	${}^{4}_{2}\mathrm{He}$ or ${}^{4}_{2}\alpha$	${}^{0}_{-1}\mathrm{e}$ or ${}^{0}_{-1}\beta$	γ
Charge	$+2$	-1	0
Mass	about 4 u	about $\frac{1}{1836}$ u	0
Speed	about 5% of the speed of light	up to 99% of the speed of light	speed of light, 3×10^{8} m/s
Penetrating power	least: a few cm of air; stopped by paper	more: a few m of air; stopped by a few mm of aluminium	most: reduced by thick lead or concrete
Ionizing power	most	less	least
In an electric field	bends towards the − plate	bends towards the + plate, more	not bent
In a magnetic field	bends a little	bends the other way, much more	not bent
Effect on the nucleus	$Z-2$, $A-4$	$Z+1$, A the same	no change

Check 3

Which radiation has the greatest ionizing power?

a alpha
b beta
c gamma
d all three ionize equally

Uses of nuclear radiations

Radiation that can harm living cells can also be put to work: to kill cancer cells or germs, to see inside the body or a steel pipe, to measure, and to date. In every use, the kind of radiation is chosen for its penetrating power and ionizing power.

In medicine

Treating cancer (radiotherapy). Gamma rays aimed at a tumor ionize the atoms in its cells and damage their DNA, so that the cancer cells die. In a **cobalt-60 machine**, the source is behind thick shielding, and the beam comes out through an opening onto the tumor. The machine turns around the patient, so that the beam always passes through the tumor but through each part of the healthy body around it for only a short time. Radiotherapy in Nepal began with cobalt-60 machines: at Bir Hospital in Kathmandu in 1991, Bhaktapur Cancer Hospital in 1998 and B. P. Koirala Memorial Cancer Hospital in Bharatpur in 1999. In **brachytherapy**, a small radioactive source, often iridium-192, is placed for a few minutes inside the body, right next to the tumor, through a thin tube, and then pulled back into its shielded safe.

CAREFUL

A linear accelerator is not radioactive

Most big cancer hospitals now use **linear accelerators** (LINACs) instead. They make their rays, X-rays as penetrating as gamma rays, from electricity, by firing fast electrons at a metal target. Switch one off and its rays stop at once; there is no radioactive source inside. A cobalt-60 machine is different: its source gives out gamma rays all the time, and "off" only means the source is behind its shield. Around 2020, Nepal's six radiotherapy centers had five linear accelerators and two cobalt-60 machines at work.

Seeing inside the body (nuclear medicine). A patient is given a tiny amount of a radioactive substance, a **tracer**, that collects in the organ to be studied. Gamma rays from it pass out through the body to a **gamma camera**, which builds a picture of where the tracer has gone: a bone that is healing or has cancer, a kidney that isn't working, the blood flowing through the heart. The commonest tracer is **technetium-99m**, which gives out gamma rays and almost no particles to harm the cells and loses half its activity in only 6 hours, so very little is left in the body after a day. Gamma rays are used because they get out of the body; an alpha or beta source inside would be stopped in the body, harming the cells around it without reaching the camera. Bir Hospital in Kathmandu, for example, has a nuclear medicine unit that scans patients' thyroid glands with technetium-99m.



Figure 12.4 *A brachytherapy afterloader. The radioactive source stays inside its shielded head until the staff have left the room; then the machine pushes it along a thin tube to the tumor, and pulls it back when the treatment is done. In front is a shielded container for a source, and behind it a bin for radioactive waste.*
Photo: Mouzi, CC BY-SA 3.0

Treating an overactive thyroid. The thyroid gland in the neck collects iodine. A patient swallows a capsule of **iodine-131**, which gathers in the thyroid, and its beta particles, which travel only about 2 mm in the body at most, destroy the overactive gland from inside while hardly touching anything else.

Sterilizing. Syringes, surgical gloves, bandages and stitches are sealed in their packets and then exposed to strong gamma rays from cobalt-60. The rays pass through the packaging and kill every germ inside, without heating anything, so plastic items that would melt in boiling water can be sterilized, and they stay germ-free until the packet is opened.

In industry

Measuring thickness. In a factory making paper, plastic sheet or aluminium foil, a beta source sits on one side of the moving sheet and a detector on the other. If the sheet comes out too thick, fewer beta particles get through; the counter notices and the rollers are pressed closer together. Beta is chosen because a thin sheet absorbs part of it: alpha would be stopped completely by any sheet, and gamma would pass through almost unchanged, whatever the thickness. For thick steel sheet, gamma rays are used instead.

Checking welds and castings (gamma radiography). A gamma source on one side of a welded steel pipe, and a photographic film on the other, give a picture like an X-ray: a crack or air bubble inside the metal lets more rays through and shows up dark. Gamma is used because only gamma gets through thick metal.

Finding leaks. A little radioactive tracer that gives out gamma rays is added to the liquid in a buried pipe. Where the pipe leaks, the tracer soaks into the ground, and a detector carried along the surface finds the spot without digging up the whole pipe.

Smoke detectors. Many smoke detectors contain a tiny amount of **americium-241**, an alpha source. Its alpha particles ionize the air between two metal plates, and the ions carry a small current between them. When smoke gets in, the ions stick to the smoke particles, the current drops, and the alarm sounds. Alpha is used because it ionizes air strongly, and because it is stopped by a few centimeters of air and by the detector's plastic case, so it is safe on a ceiling.