Chapter 23: Radioactivity

23.1 Introduction

Radioactive substance:

1. A substance that decays by emitting radiation from its atomic nuclei is radioactive.
2. There are two ways in which radioactive substances can pose problems:
   a. If a radioactive substance enters our bodies, its emitted radiation can cause harm, resulting in contamination.
   b. Exposure to radiation or radioactive substances can also irradiate our bodies, leading to exposure to radiation doses.

Radiation:

1. **Energy** spreading out from a source carried by particles or waves.

Sources of natural background radiation:

1. The air contains a radioactive gas called radon, which originates from radioactive uranium rocks underground and seeps up to the Earth's surface.
2. Radioactive substances are present in the ground. When we use materials sourced from the ground for construction, such as building houses, we are exposed to radiation from these substances.
3. Radiation also reaches us from space in the form of cosmic rays.

Sources of artificial background radiation

1. Most radiation from artificial sources emanates from medical procedures, including:
   a. X-rays
   b. Gamma rays used for cancer treatment by destroying cancer cells.
2. Professionals such as medical radiographers and staff at nuclear power stations work directly with radiation as part of their duties.

Detecting radiation

1. Radiation can be measured using a Geiger counter.
2. The Geiger counter records the rate at which radiation is detected.
3. This rate is known as the count rate and is typically measured in counts per second (count/s) or counts per minute (count/min).

23.2 Radioactive decay

1. The process in which an **unstable** nucleus gives out radiation to become more stable.

   Unstable = Strong nuclear forces do not generate enough binding energy to hold the nucleus together permanently.

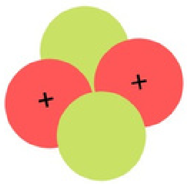
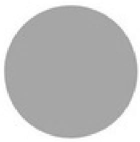
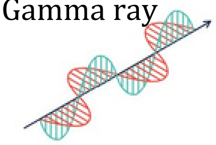
   Why are some nuclei unstable?

a. They contain too many protons b. They contain too many neutrons

   An unstable nucleus emits **radiation** in order to become more stable.

2. Radioactive decay is a random process, and the direction in which radiation is emitted is also random.
3. Radioactive decay is not influenced by external factors such as temperature.

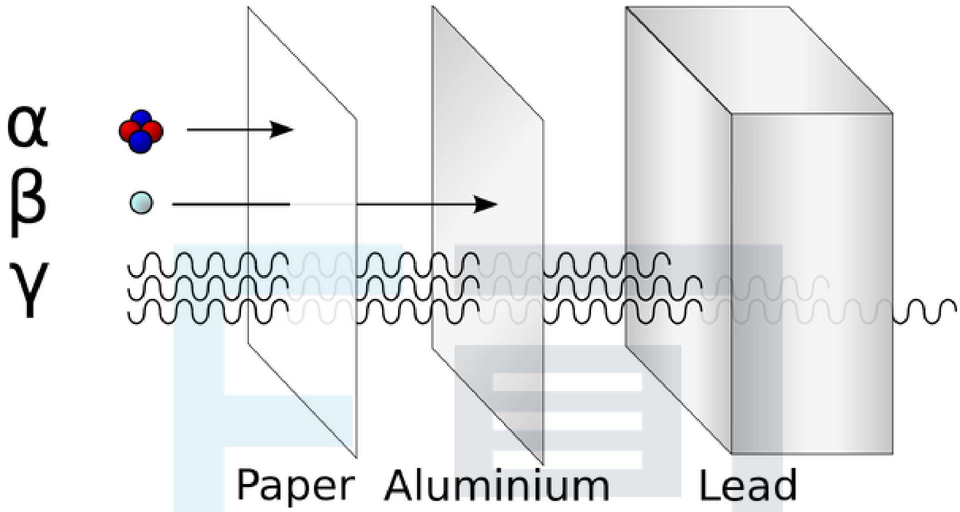
Three types of radiation

Name	Symbol	Made of	Charge
Alpha Particle 	α	2 protons + 2 neutrons	Positive
Beta Particle  It is an electron *from inside the nucleus.*	β	An electron	Negative
Gamma ray  It is a form of electromagnetic radiation with a very short wavelength and high frequency.	γ	Electromagnetic radiation	Neutral

1. An atom of a radioactive substance can emit an α-particle, a β-particle, or a γ-ray as part of its decay process.
2. When an atom of a radioactive substance decays by emitting an α-particle or a β-particle, it transforms into an atom of another element because the number of protons in the nucleus changes during the decay process.

Penetrating power

1. Radiation can pass through **solid** materials.
2. Different radiation can penetrate different thicknesses of materials.



3. Alpha particle

- Alpha particles are easily absorbed and can be stopped by a thin sheet of paper.
- Alpha particles cannot penetrate the outer layer of human skin.

4. Beta particle

- Beta particles can travel relatively easily through air or paper.
- They can be absorbed by a few millimeters of metal, such as aluminum.

5. Gamma radiation

- Gamma radiation is the most penetrating type of radiation.
- It requires several centimeters of dense materials like lead, or several meters of concrete, to effectively absorb most gamma radiation.

Ionization

1. Radiation can knock electrons out of atoms, resulting in the formation of ions. This process is known as ionization.
2. The radiation emitted by the nuclei of radioactive substances causes ionization in the materials it interacts with. Therefore, it is often referred to as ionizing nuclear radiation.
3. Ionizing effect of each radiation:

Name	Mass	Speed	Charge	Description
α	Mass of proton x 4	(m/s) 3 x 107	+2	• **<u>Slowest</u>** moving • Has the **<u>largest</u>** charge • May knock an electron from the air molecule, so it becomes charged. It then loses a little of its energy
β	$\frac{mass\ \ of\ \ proton}{1840}$	2.9 x 10^{8}	-1	• Less ionizing compared to alpha. (a) less charge (b) Move **<u>faster</u>**, this means that it is more likely to travel straight past an air molecule without interacting with it • They can travel further in air without getting absorbed

γ	0	3×10^8	0	• It is uncharged and moves fastest of all • Least readily absorbed in air • Least ionizing

Relationship between ionizing power and absorption

- Alpha (α) radiation is highly ionizing, making it easily absorbed and the least penetrating.
- Gamma (γ) radiation is weakly ionizing, making it less easily absorbed and the most penetrating.

Radioactive decay equations

1. Radioactive decay can be described using balanced equations with the nuclear notation we used in Chapter 22.
2. Types of decay:
   - **α-decay**
   - **β-decay**
   - **γ-decay**

α-decay

1. The decay of a radioactive nucleus by emitting an α-particle involves the emission of two protons and two neutrons.
2. During α-decay, the proton number (atomic number) of the nucleus decreases by 2, and the nucleon number (mass number) decreases by 4.
3. Example:

$$^{241}_{94}Am \rightarrow ^{237}_{92}U + ^{4}_{2}He + \text{energy}$$

- This equation represents the decay of **americium-241**, the isotope used in smoke detectors.
- Americium-241 emits an alpha particle (which is essentially a helium nucleus).
- The proton number (atomic number) and nucleon number (mass number) must be conserved before and after the decay.

β-decay

1. The decay of a radioactive nucleus by the emission of a β-particle.
2. Example:

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

- This is the decay that is used in radiocarbon dating.
- A carbon-14 nucleus decays to become a nitrogen-14 nucleus.
- The **β-particle** is represented by $^{0}_{-1}e$
- But where does the extra proton and electron come from?

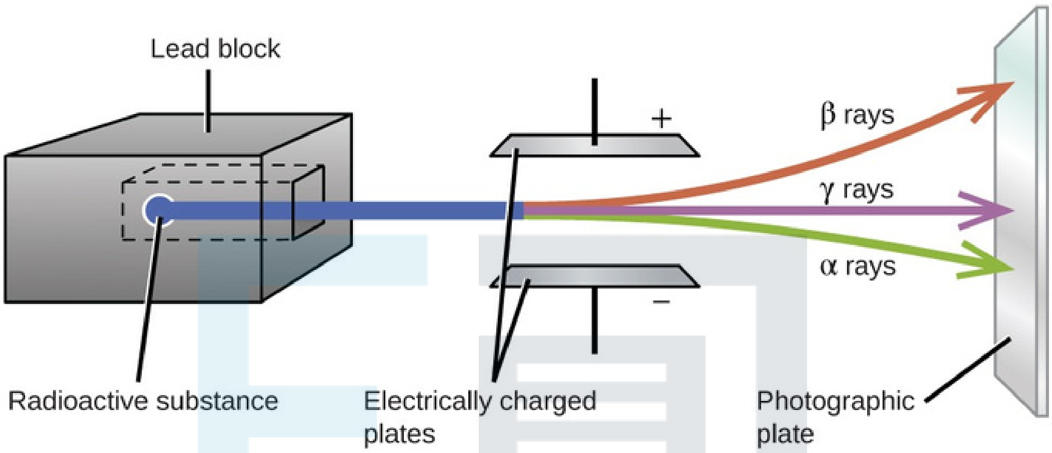
Answer: A single neutron split into a proton and an electron.

$$^{1}_{0}n \rightarrow ^{1}_{1}p + ^{0}_{-1}e$$

Note: In a radioactive decay, nucleon number and proton number are conserved.

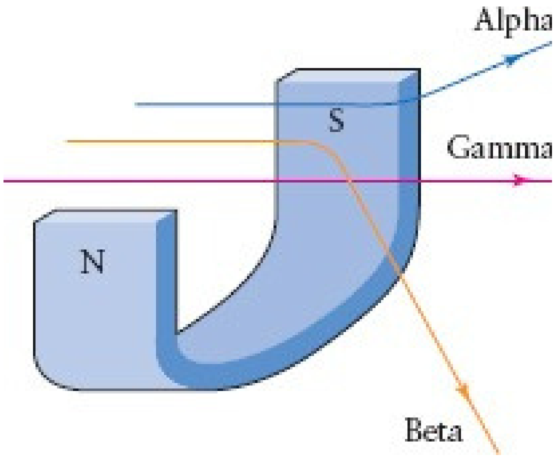
Deflecting radiation

1. We can distinguish between the three types of radiation by observing their responses to electric and magnetic fields.
2. Experiment 1:



- Alpha (α) particles, which are positively charged, are attracted towards a negatively charged plate.
- Beta (β) particles, being negatively charged, are attracted towards a positively charged plate.
- Beta particles are more deflectable compared to alpha particles due to their lighter mass.
- Gamma (γ) rays remain undeflected as they are uncharged.

3. Experiment 2:

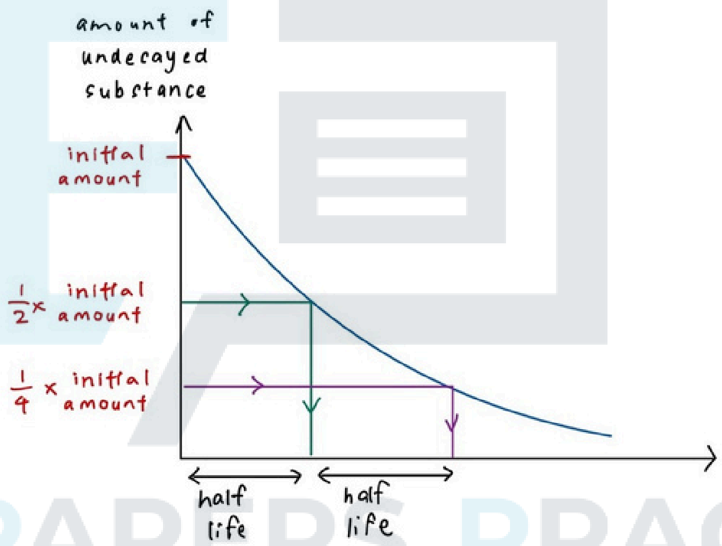


- Alpha (α) particles and beta (β) particles carry electric charges, thus constituting an electric current when they move.
- Due to their opposite charges, they experience forces in opposite directions when in a magnetic field.
- The direction of deflection of these particles can be determined using Fleming's left-hand rule.

23.3 Activity and half-life

Activity

1. The activity of a radioactive source refers to the rate at which its nuclei decay.
2. Over time, the activity of a source decreases because as unstable nuclei decay and become stable, there are fewer remaining unstable nuclei, resulting in fewer decays per second.
3. Decay graph:



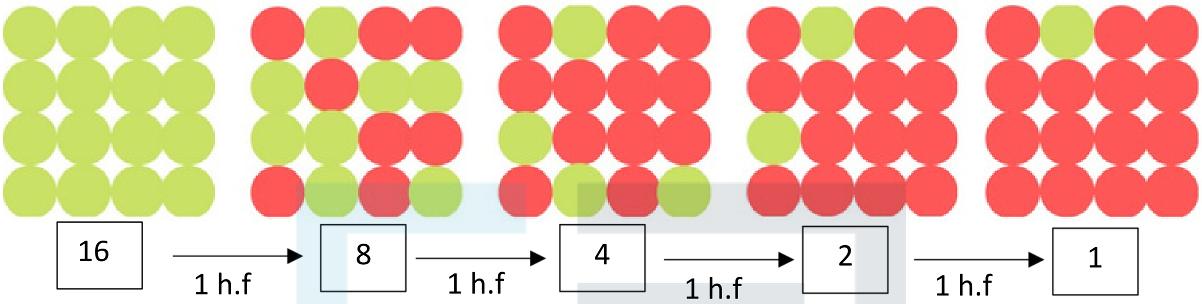
- The graph illustrates that the radioactive substance decreases rapidly initially, followed by a slower decline over time.
- As the graph shows a gradual tapering off, it becomes challenging to predict when the last atoms will decay precisely.
- Different radioactive substances decay at varying rates.

Half Life

1. The half-life of a radioactive isotope is defined as the average time taken for half of the atoms in a sample to decay, or alternatively, the time it takes for the activity or count rate of the sample to halve.
2. Half-lives can vary significantly, ranging from fractions of a second to thousands of years, depending on the specific radioactive isotope.

Half Life misconception

1. After one half-life, **half** of the atoms in a radioactive sample have decayed.
2. However, this does not mean that all of the atoms will have decayed after two half-lives.
3. The idea of a half-life is more like this:



Worked Example

Polonium-210 has a half-life of 138 days. The count rate of a sample is 550 count/s.

How long will it take for the count rate to drop to 40 count/s?

Corrected count rate

1. The count rate recorded by a Geiger counter typically includes both the background radioactivity and the count rate from the radioactive source. In many cases, the background count is minimal compared to the activity of the source.
2. If the background count is being considered, it should be **subtracted** from the Geiger counter measurements.

corrected count rate = measured count rate – background count rate

Past Year Questions

The count rate of a radioactive material is measured using a detector. The reading on the detector is 88 counts per second. The background count rate is 40 counts/second.

The half-life of the radioactive substance is 12 hours. What is the reading on the detector after 24 hours?

23.4 Usages of radioisotopes

1. We will look at the uses of radioisotope in 4 separate groups:

A. Uses related to penetrating power

i. **Smoke detector**

- The radioactive material in a smoke detector is Americium-241, which emits α-radiation and has a half-life of 430 years. This means that the detector's count rate for this substance will remain fairly consistent over the duration of its use.
- How it works:
  - A smoke detector works by using a small amount of radioactive material (usually americium-241) that emits alpha particles. When smoke enters, it interrupts the alpha particles' path, causing a drop in electrical conductivity in the detector, triggering an alarm to alert of potential fire.

ii. **Thickness measurement**

- In industry, **β-radiation** is often used in to measure thickness.
- How:
  - Beta radiation is used to measure paper thickness by emitting beta particles through a radioactive source towards the paper. A detector on the opposite side measures the intensity of beta particles that pass through.

Thicker paper absorbs more beta particles, resulting in a lower detected intensity, providing a measurement of paper thickness.

- **β-radiation** is the most suitable. **α-particle** would be absorbed entirely by the paper, **γ -ray** and would hardly be affected, because it is the most penetrating.

- Steel factory uses **γ -ray.**

iii. <u>Fault detection</u>

- **γ -ray** is sometimes used to detect faults in manufactured goods.

B. <u>Uses related to cell damage – radiation therapy</u>

i. <u>Cancer treatment</u>

Gamma rays in cancer treatment, often emitted from a radioactive source like cobalt-60 or produced by linear accelerators, target and destroy cancerous cells. These high-energy rays penetrate deeply into the body, damaging DNA within cancer cells to inhibit their growth and ultimately lead to cell death, helping to shrink tumours and manage cancer.

ii. <u>Food irradiation</u>

Gamma rays in food irradiation are generated from a radioactive source such as cobalt-60 or cesium-137. These rays penetrate food products, disrupting the DNA of bacteria, insects, and other pathogens, which reduces spoilage and extends shelf life. The process does not make food radioactive but enhances safety by reducing harmful microorganisms and pests.

iii. **Sterilization**

Gamma rays ensure sterilization of medical equipment by penetrating packaging and material to destroy microorganisms' DNA. Using a gamma radiation source, such as cobalt-60, items are exposed to controlled doses that eliminate bacteria, viruses, and spores. This method ensures high effectiveness without heat or chemical residues, crucial for medical safety.

C. Uses related to detectability – radioactive tracing

i. Medicine

- Some diseases can be diagnosed using γ-radiation.
- A radioactive chemical is injected into the patient, and a scanner tracks its movement.
- For example, to detect kidney blockage, technetium-99, a radioactive tracer, is injected into the bloodstream. If there's a blockage in the kidney, the tracer won't pass through, signaling the presence of a blockage. Technetium-99 has a short half-life, ensuring safety during this diagnostic procedure.

ii. Engineering

- Engineers may want to trace underground water flow.

To prevent toxic water from a new waste dump from contaminating the local water supply, engineers employ a method where water containing a radioactive substance is injected into a deep hole under high pressure. The movement of this water through underground fissures is then monitored using a γ-detector at ground level. This approach enables engineers to monitor water flow and pinpoint potential pathways that might lead to contamination of the local water supply.

D. Uses related to radioactive decay – half-life and radiocarbon dating

1. Knowing the rate of decay of radioactive substances, we can use them to discover how old objects and materials are.
2. Radiocarbon dating:

Radiocarbon dating is a method used to determine the age of organic materials by measuring the decay of the radioactive isotope carbon-14.

3. How it works:

- Carbon exists in all living organisms, and upon their death, the carbon-14 within their bodies starts to undergo decay. As time passes, the quantity of carbon-14 in the organism diminishes. By understanding carbon-14's half-life (5700 years), scientists can gauge the remaining amount of carbon-14 in the organism and approximate its age when it was alive. This method is widely applied in archaeology and other disciplines to determine the age of various materials and artifacts.

4. Two ways to measure the amount of carbon-14 present in an object:

   a. Measure the activity of the sample using a detector such as a **Geiger counter.**
   b. By counting the number of carbon-14 atoms using a **mass spectrometer**

5. Two challenges with radiocarbon dating are variations in the amount of carbon-14 present in the atmosphere in the past and the additional carbon-14 introduced into the atmosphere from nuclear weapons testing during the 1950s and 1960s.

23.5 How to use radioactive material safely

1. Any element comes in several forms or isotopes.
2. Unstable isotopes are known as **radioisotopes.**

A radioactive isotope of an element.

3. There are three ways radiation can damage living cells:

a. Killing a cell

When someone experiences radiation burns, a high dose of radiation causes extensive ionization within cells, potentially resulting in cell death. This damage occurs when cells are exposed to significant radiation levels, leading to the development of radiation burns.

b. Cause cancer

Damage to the DNA within the cell nucleus can disrupt the cell's regulatory mechanisms. This disruption may lead to uncontrolled cell division, potentially resulting in the formation of a tumor.

c. Genetic mutations

If a gamete is affected by radiation and its DNA is damaged, this damage can potentially be passed on to future generations. This may result in genetic mutations that could cause developmental issues in a fertilized egg or lead to the birth of a baby with a genetic disorder.

4. Alpha particles
    - Alpha particles pose the least external harm due to their low penetration capability, typically being stopped by the outer layer of dead skin.
    - However, if an alpha-emitting source enters the body, it can cause significant damage because of its high ionization potential.
    - Inhaling radon and thoron gases can lead to internal radiation exposure in the lungs, potentially resulting in lung cancer.
5. Learning how to reduce the hazards of radiation means that we can learn to live safely with it and put it to many **worthwhile** purposes.

6. Safety precautions when dealing with radioactive material.

Safety precaution	Explanation
Workers in contaminated areas wear protective suits	Radiation can be absorbed by protective suits, and the choice of materials varies based on the type of radiation. For gamma rays, suits lined with lead are commonly used to provide effective shielding.
Radioactive hazard labels	These warning signs inform individuals about the potential hazard, allowing them to maintain a safe distance and limit their exposure time to the source.
Photographic film dosimeter badges	These devices are employed to monitor the amount of radiation exposure a person receives. When a safe limit is reached, workers may need to be relocated to different areas to minimize further exposure.
Record keeping	Schools must document the duration of use and personnel responsible for radioactive sources to prevent excessive exposure.
Remote operating of scanners	The scanner operator usually operates the scanner from a remote location, which increases the distance between them and the radiation source. Additionally, they may be shielded by a screen or barrier that absorbs some of the radiation, further minimizing exposure.
Storage boxes for sources	Radioactive sources should be stored safely, often within lead containers to absorb the majority of radiation emitted.

Past Year Questions

No	Questions

1

A student carried out an experiment to find the half-life of a radioactive substance.
Their results are shown in the table below.

time (seconds)	count-rate from source (counts per second)
0	300
20	200
40	150
60	100
80	75

What is the half-life of this substance?

A 20 seconds.

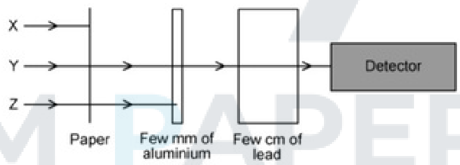
B 40 seconds

C 60 seconds

D 80 seconds

2

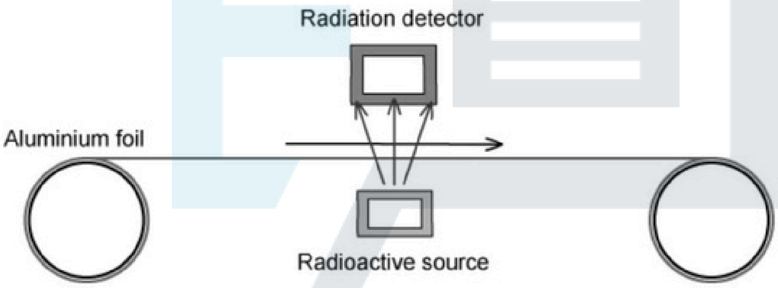
A student has three radioactive sources **X**, **Y** and **Z**. They devised the following experiment to determine what type of radiation each source is emitting.



The student found that the radiation from **X** was stopped by a sheet of paper, **Y** was partially stopped by a few cm of lead and **Z** was stopped by a few mm of aluminium.

Which of the following correctly identifies each type of radiation

	X	Y	Z
A	α-particle	β-particle	γ-ray
B	α-particle	γ-ray	β-particle
C	γ-ray	β-particle	α-particle
D	β-particle	γ-ray	α-particle

3	Which statement is **not** a method used to minimise the risk caused by working with radioactive sources. **A** Store the sources in lead-lined boxes. **B** Minimise the amount of time spent handling the sources. **C** Keep the source cold. **D** Keep the source as far away as possible, for example, using a pair of tongs.
4	Radioactive sources are often used in industry as part of manufacturing processes. The diagram below shows radiation being used to measure the thickness of a sheet of aluminium foil. The detector feeds back to the rollers to adjust the thickness.  What type of radiation would be the most suitable for this purpose? **A** α-particles **B** β-particles **C** γ-rays **D** All of the above.
5	An nucleus of Uranium ($^{238}_{92}U$) is unstable and decays by emitting an **α**-particle. Which equation correctly describes this process? **A** $^{238}_{92}U \rightarrow \, ^{4}_{2}\alpha + \, ^{234}_{90}Th$ **B** $^{238}_{92}U \rightarrow \, ^{4}_{2}\alpha + \, ^{234}_{90}U$ **C** $^{238}_{92}U + \, ^{4}_{2}\alpha \rightarrow \, ^{234}_{90}Th$ **D** $^{238}_{92}U \rightarrow \, ^{4}_{2}\alpha + \, ^{234}_{88}Ra$

6	A radioactive substance has a half-life of 4 days. It is currently emitting 8000 β-particles per minute. How many β-particles will it emit per minute after 12 days? **A** 4000 **B** 2000 **C** 1000 **D** 667

Answer: B,B,C,B,A, C