# 26 Radioactivity

## 26.1 The Discovery of the Nucleus

### $\alpha$ Particle Scatter Experiment

It was known that $\alpha$ radiation consists of **fast-moving positively charged particles**.

1. Using a **narrow beam** of $\alpha$ particles all of the **same energy**.
2. A **thin metal foil** is placed in the path of the beam.
3. $\alpha$ particles scattered by the metal foil were detected by a detector which could be moved around at a constant distance from the point of impact of the beam on the metal foil.

The result showed that

- Most $\alpha$ particles pass straight through the foil with **little to no deflection**.
- About 1 in 2000 were deflected.
- 1 in 10000 $\alpha$ particles were deflected through angles of more than 90°.

It can be concluded that

- Most of the atom's mass is **concentrated in a small region** called the nucleus, in the centre of the atom.
- The nucleus is **positively charged** because it repels $\alpha$ particles that approaches it too closely.

### Estimation of Size of the Nucleus

For a **single scattering** by a foil of $n$ layers of atoms, the probability of an $\alpha$ particle being deflected by a given atom is 1 in $10000n$.

For a nucleus of diameter $d$ in an atom of diameter $D$

$$\frac{\frac{1}{4}\pi d^2}{\frac{1}{4}\pi D^2} = \frac{1}{10000n}$$

$$d^2 = \frac{D^2}{10000n}$$

A typical value of $n = 10^4$ gives $d = \dfrac{D}{10000}$.

## 26.2 The Properties of $\alpha$, $\beta$ and $\gamma$ Radiation

Rutherford found that radiation emitted

- **Ionises air**, making it conduct electricity.
- Is of three types, $\alpha$, $\beta$ and $\gamma$.
- A **magnetic field** deflects $\alpha$ and $\beta$ radiation in opposite directions, and has no effect on $\gamma$ radiation.

### Ionisation Experiments

The ionising effect of each type of radiation can be investigated using an **ionisation chamber** and a **picoammeter**, containing air at atmospheric pressure.

Ions created in the chamber are attracted to oppositely charged electrodes where they are discharged, causing a current proportional to the number of ions per second created.

- $\alpha$ radiation causes **strong ionisation**.

  Ionisation ceases beyond a certain distance, because $\alpha$ radiation has a range in air no more than a few centimetres.

- $\beta$ radiation is **muck weakly ionising**, and range in air up to a metre.

  A $\beta$ particle therefore produces **less ions per millimetre** along its path than an $\alpha$ particle does.

- $\gamma$ radiation has a **much weaker ionising effect** than $\alpha$ or $\beta$ radiation. This is because photons carry no charge, so have less effect.

### Cloud Chamber Observations

A cloud chamber contains air **saturated with vapour** at a very low temperature.

An $\alpha$ or $\beta$ particle passing through the cloud chamber leaves a **visible track of condensed vapour droplets**.

- $\alpha$ particles create straight tracks and are easily visible.

  The tracks from a given isotope are **all of the same length**, indicating they have the same range.

- $\beta$ particles produced **wispy tracks** and are **easily deflected** as a result of collisions with air molecules.

  The tracks are not as easy to see as $\alpha$ particle tracks.

### Absorption Tests

A **Geiger tube and a counter** is used to investigate absorption by different materials. Each particle of radiation that enters the tube is registered by the counter as a single count.

The **count rate** is the number of counters divided by time taken.

1. The count rate due to background radioactivity is measured.
2. The count rate is then measured with the source at a **fixed distance** from the tube, **without any absorber** present.

   The **corrected count rate** is the background count rate subtracted from the count rate with source present.
3. The count rate is then measured with the **absorber present** between the source and the tube.
4. The corrected count rate with and without the absorber present can then be compared.

### The Geiger Tube

The Geiger tube is a **sealed metal tube**, containing

- **Argon gas** at low pressure.
- A tiny mica window at the end to allow $\alpha$ and $\beta$ particles in.
- A **metal rod** with positive potential down the middle of the tube.
- **Tube walls** are connected to the negative terminal of the power supply.

When a particle of ionising radiation enters the tube,

- The particle ionises the gas atoms along its track.
- **Negative ions** are attracted to the tube, and **positive ions** to the wall.
- The ions accelerate and collide with other gas atoms, **producing more ions**.
- Causing many ions to **discharge at the electrodes**.
- A **pulse of charge** passes round the circuit through resistor $R$, causing a **voltage pulse** which is recorded as a single count by the **pulse counter**.

## 26.3 More about $\alpha$, $\beta$ and $\gamma$ Radiation

- $\alpha$ radiation consists of **positively charge particles** - each $\alpha$ particle is composed of two protons and two neutrons.
- $\beta$ radiation from naturally occurring radioactive substances consists of **fast-moving electrons**.

This is proved by measuring the **deflection of a beam of $\beta$ particles**, which is used to work out the **specific charge** of the particles, to be the same as the electron.

A nucleus with too many proton emits a **positron**.

- $\gamma$ radiation consists of photon.

  A $\gamma$ photon is emitted if a nucleus has excess energy after it has emitted an $\alpha$ or $\beta$ particle.

### Inverse Square Law for $\gamma$ Radiation

The **intensity** of radiation is the **radiation energy per second** passing normally through unit area.

- For a point source that emits $n$ $\gamma$ photons per second, each energy $hf$, radiation energy per second from the source is $nhf$.
- At distance $r$ from the source, all photons pass through a total area of $4\pi r^2$.

$$I = \frac{nhf}{4\pi r^2}$$

### Equations for Radioactive Change

- $\alpha$ emission: ${}^A_Z X \rightarrow {}^4_2\alpha + {}^{A-4}_{Z-2}Y$
- $\beta^-$ emission: ${}^A_Z X \rightarrow {}_{Z+1}^{\;\;A}Y + {}^{\;\,0}_{-1}\beta + \bar{\nu_e}$
- $\beta^+$ emission: ${}^A_Z X \rightarrow {}_{Z-1}^{\;\;A}Y + {}^{\;\,0}_{+1}\beta + \nu_e$
- Electron capture: ${}^A_Z X + {}^{\;\,0}_{-1}e \rightarrow {}_{Z-1}^{\;\;A}Y + \nu_e$

## 26.4 The Dangers of Radioactivity

Ionising radiation is hazardous because it **damage living cells**.

- Destroy cell membrane which causes cells to **die**.

  High doses of ionising radiation kill living cells.

- Damage vital molecules such as DNA to cause cells to **grow uncontrollably or mutate**.

  Cell mutations and cancerous growth occurs at low and high doses.

### Radiation Monitoring

Anyone using equipment that produces ionising radiation must wear a **film badge** to monitor his exposure to ionising radiation.

- Different areas of the film are covered by absorbers of different material and different thickness.

- When the film is developed, the amount of exposure to each form of ionising radiation can be estimated from the blackening of the film,
- If the film is overexposed, the wearer is not allowed to continue working with the equipment.

**Dose** is measured in energy absorbed per unit mass of matter from the radiation.

#### Background Radiation

Background radiation occurs naturally due to **cosmic radiation** and from **radioactive materials**.

**Storage**: radioactive materials should be in **lead-lined containers**. The lead lining must be thick enough to reduce the $\gamma$ radiation from the source in the container to about the background level.

No source should be allowed to come into contact with the skin.

- **Solid sources** should be transferred using handling tools or handling robots to ensure the material is **as far from the user as practicable**.

  So the user is beyond the range of $\alpha$ and $\beta$ radiation of the source, and the $\gamma$ radiation at the user is as low as possible.
- Liquid, gas and solid in powdered form should be in **sealed containers**, so radioactive gas cannot be breathed in, liquid splashed or drunk.
- Radioactive sources should not be used for longer than necessary.

## 26.5 Radioactive Decay

The **decay curve** shows the mass of the initial isotope decreases gradually as the number of nuclei of the isotope decreases. The mass **decreases exponentially**, which means the mass drops by a constant factor in equal intervals of time.

The **half-life** $T_{1/2}$ of a radioactive isotope is the time taken for the mass of the isotope to decrease to half the initial mass.

The mass decreases exponentially, because radioactive decay is a **random process** and the number of nuclei that decay in a certain time is in proportion to the number of nuclei remaining.

#### Activity

The activity $A$ of a radioactive isotope is the number of nuclei of the isotope that disintegrate per second - the rate of change of the number of nuclei of isotope.

The unit of activity is the **becquerel** (Bq), $1\mathrm{Bq} = 1$ disintegration per second.

- The activity of a radioactive isotope is **proportional to the mass** of the isotope.
- The mass of a radioactive isotope **decreases with time**, so the activity decreases with time.

**Activity and Power**

For a radioactive source of activity $A$ that emit particles of the same energy $E$.

$$P = AE$$

## 26.6 The Theory of Radioactive Decay

The decay of an unstable nucleus is an **unpredictable event**, every nucleus of a radioactive isotope has an **equal probability of undergoing radioactive decay** in any given time interval.

For a large number of nuclei of a radioactive isotope, the number of nuclei that disintegrate in a certain time interval depends only on the total number of nuclei present.

The **rate of disintegration**

$$\frac{dN}{dt} = -\lambda N$$

where $\lambda$ is the **decay constant**.

So the activity $A$ of $N$ atoms of a radioactive isotope is given by

$$A = N\lambda$$

From the rate of disintegration, we have

$$N = N_0 e^{-\lambda t}$$
$$m = m_0 e^{-\lambda t}$$
$$A = A_0 e^{-\lambda t}$$

The **corrected count rate** $C$ due to a sample of radioactive isotope at a fixed distance from a Geiger tube is **proportional to the activity** of the source.

$$C = C_0 e^{-\lambda t}$$

where $C_0$ is the count rate at time $t = 0$.

### The Decay Constant

The decay constant $\lambda$ is the probability of an individual nucleus decaying per second.

$$\lambda = \frac{\Delta N}{N} / \Delta t$$

And

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

## 26.7 Radioactive Isotopes in Use

The choice of an isotope for a particular purpose depends on

- Its **half-life**.
- The **type of radiation** it emits.

### Carbon Dating

1. Carbon dioxide from the atmosphere is **taken up by living plants**, a small percentage of the carbon content of any plant is the radioactive carbon-14.
2. Once a tree has died, no further carbon is taken in, so the proportion of carbon-14 in the dead tree decreases as the carbon-14 nuclei decay.
3. The age of the tree can be calculated by **measuring the activity** of the dead sample. Provided the activity of the same mass of living wood is known.

### Argon Dating

Ancient rocks contains **trapped argon gas** as a result of the decay of radioactive isotope of potassium. The age of the rock can be calculated by measuring the proportion of argon-40 to potassium-40.

### Radioactive Tracers

A radioactive tracer is used to follow the path of a substance through a system.

The radioactive tracer should

- Have a half-life which is stable enough for the necessary measurements to be made, and short enough to decay quickly after use.
- Emit $\beta$ or $\gamma$ radiation so it can be detected outside of the flow path.

## 26.8 More about Decay Modes

### The N-Z Graph

The N-Z graph is a graph of the neutron number $N$ against the proton number $Z$ for all known isotopes.

- **Light isotopes** ($Z < 20$) follow the straight line $N = Z$, such nuclei have an equal number of protons and neutrons.
- For $Z > 20$, stable nuclei have **more neutrons and protons**. The extra neutrons help bind the nucleons together without introducing repulsive electrostatic forces, which adding more protons would do.
- $\alpha$ emitters occur beyond $Z = 60$, they have more neutrons than protons but they are too large to be stable. The strong nuclear force is **unable to overcome the electrostatic force of repulsion** between two protons.
- $\beta^-$ emitters occur to the left of the stability belt where isotopes are **neutron-rich** compared to stable isotopes.
- $\beta^+$ emitters occur to the right of the stability belt where the isotopes are **proton-rich** compared to stable isotopes.

### Nuclear Energy Levels

If the daughter nucleus is formed in an **excited state** after it emits an $\alpha$ or $\beta$ particle or undergoes electron capture, the nucleus moves to its **ground state** either directly or via one or more lower-energy excited states.

The short-lived excited state is said to be a **metastable state**.

## 26.9 Nuclear Radius

We can estimate the diameter of different nuclides using **high-energy electrons**.

- When a **beam of high-energy electron** is directed at a thin solid sample of an element, the incident electrons are **diffracted by the nuclei** of the atoms in the foil.
- The electrons are diffracted because the de Broglie wavelength of such high-energy electrons is about the same as the diameter of the nucleus.
- A detector is used to measure the number of electrons per second diffracted through different angles.

Result shows

- **Scattering** of the beam electrons by the nuclei occurs due to their charge, this causes the intensity to decrease as angle $\theta$ increases.

- **Diffraction** of the beam electrons by each nucleus causes intensity maxima and minima to be superimposed on the scattering patter.

  The angle of the first minimum $\theta_{\text{min}}$ is measured and used to calculate the diameter of the nucleus. Provided the wavelength of the incident electrons is known.

### Nucleon Radius and Nucleon Number

It can be shown that $R$ depends on mass number $A$ according to

$$R = r_0 \sqrt[3]{A}$$

where $r_0 = 1.05\text{fm}$.

The graph of $\ln r$ against $\ln A$ gives

- A straight line of gradient $1/3$
- With y-intercept $\ln r_0$.

### Nuclear Density

Assuming the nucleus is spherical.

$$\begin{aligned} \text{Volume } V &= \frac{4}{3}\pi R^3 \\ &= \frac{4}{3}\pi (r_0 \sqrt[3]{A})^3 \\ &= \frac{4}{3}\pi {r_0}^3 A \end{aligned}$$

This means the **nuclear volume** $V$ is proportional to the mass of the nucleus.

- The density of the nucleus is constant, independent, and same throughout a nucleus.
- We can conclude that nucleons are **separated by the same distance** regardless of the size of the nucleus, and therefore evenly separated inside the nucleus.

$$\rho_{\text{nuc}} = \frac{Au}{\frac{4}{3}\pi {r_0}^3 A}$$