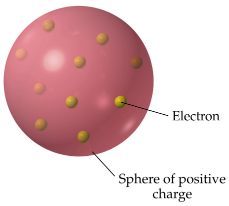
Radioactivity

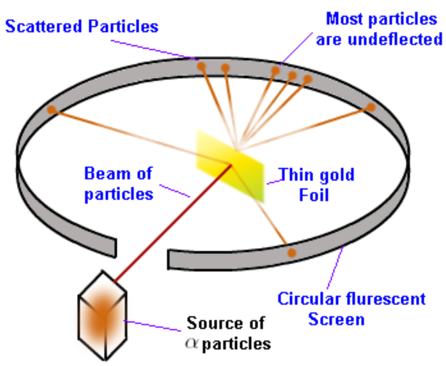
1 Rutherford Scattering

1.1 The plum pudding model



The plum pudding model was the initial model of the atom, stating a sphere of positive charge with electrons embedded into it.

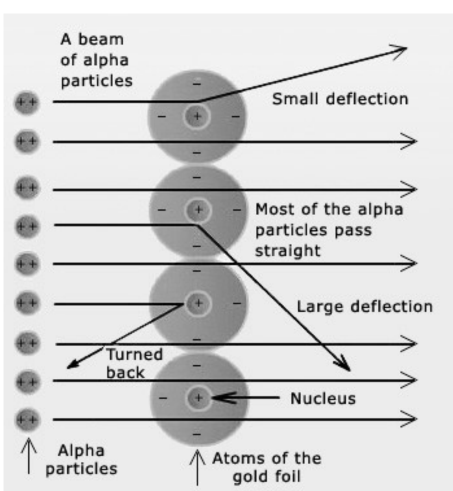
1.2 Rutherford's experiment



Rutherford's experiment involved firing a beam of alpha particles at gold foil and measuring the paths of particles from the foil.

- Gold was used as it was expected to have a large nucleus
- The screen fluoresces when collided with
- This showed the atom was mostly empty space with a positive nucleus

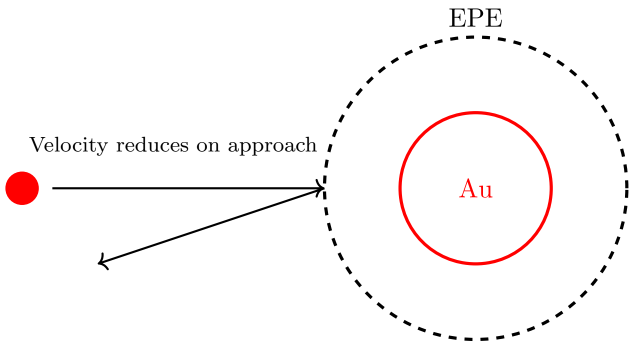
1.2.1 Results



Observation	Explanation
Most electrons pass all the way through	Atoms are mostly empty space
Some are deflected	The atom has a positive centre
Some are deflected by significant angles	The positive charge is condensed in a small area

1.3 Estimating the size of the nucleus

1.3.1 Closest approach method



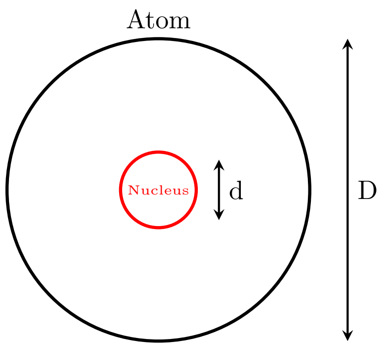
KE=EPE

$$8.0 \times 10^{-13} = \frac{1}{4\pi\epsilon_0} \times \frac{Q_{Au}}{r} \times Q_\alpha$$

$$r = 4.55 \times 10^{-14}$$

1.3.2 Estimate from scattering data

- About $\frac{1}{10{,}000}$ deflected through more than 90°
- Foil had n layers of atoms



$$\frac{\frac{1}{4}\pi d^2}{\frac{1}{4}\pi D^2} = \frac{d^2}{D^2} = \frac{1}{10,000n}$$

$n = 10^4$ layers

$$\frac{d^2}{D^2} = \frac{1}{10,000 \times 1 \times 10^4}$$

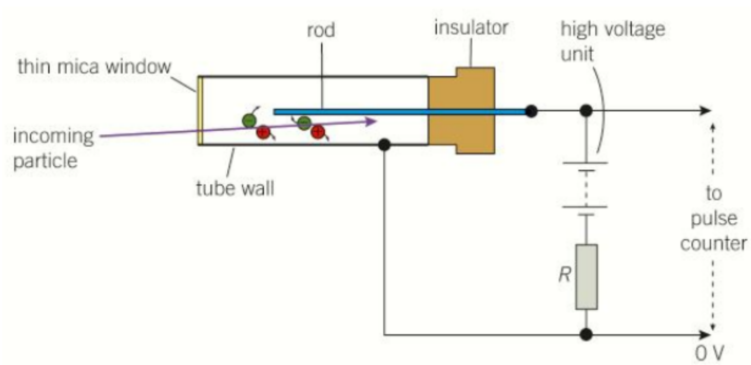
$$d = \frac{D}{10,000}$$

2 Radioactive materials

2.1 Sources of background radiation by most common

1. Air (e.g. radon gas)
2. Medical
3. Ground and buildings
4. Food and drink
5. Cosmic rays
6. Nuclear weapons
7. Air travel
8. Nuclear power

2.2 Geiger Müller tube



When a particle of ionising radiation enters the tube, the particle ionises the gas atoms along its track. The negative ions are attracted to the rod and the positive ions to the wall. These ions cause further ionisation, creating enough ions for a current to flow. A pulse of charge passes round the circuit through resistor R, causing the voltage pulse across R which is recorded as a single count by the pulse counter

The dead time of the tube, the time taken to regain its non conducting state after an ionising particle enters it, is typically of the order of 0.2ms.

3 Radioactive decay

	Alpha	Beta	Gamma
Nature	2 Protons+2 Neutrons	High speed electron or positron	High energy photon
Range	Up to 10cm	Up to 1m	Infinite
Deflection in a magnetic field	Deflected	Opposite direction to α particles and more easily deflected	Not deflected
Absorption	Paper	Aluminium	Lead
Ionisation	10^4 ions per mm	100 ions per mm	Very weak ionising effect
Energy of each particle	Constant for a given source	Varies up to a maximum for a given source	Constant for a given source

3.1 α Decay

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

3.2 β^- Decay

Neutron to proton and β^- particle

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

3.3 β^+ Decay

Proton to neutron and β^+

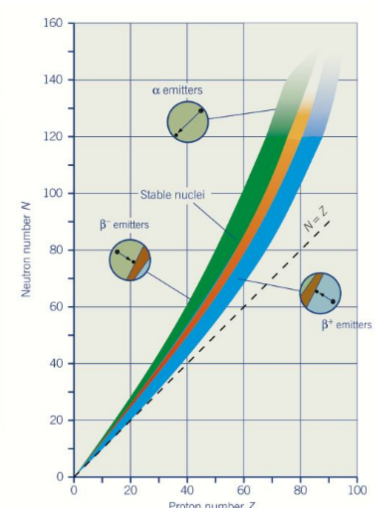
3.4 Electron Capture

Proton+Electron$\rightarrow$ Neutron

3.5 Gamma Emission

No change to the structure of the nucleus.
Often follows alpha or beta emission. Daughter nucleus can be in an excited state. It emits gamma radiation as it returns to its ground state.

3.6 NZ Plot



3.7 Half life

The half life of a radioactive substance is the time taken for half the atoms in the sample to decay.

$$\text{The rate of decay} \propto \text{The number of nuclei left}$$

$$-\frac{\Delta N}{\Delta t} \propto N$$

The LHS of this equation is called the activity and has units Bq

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

The solution to this equation

$$N = N_0 e^{-\lambda t}$$

This can also be written as:

$$\frac{N}{N_0} = e^{-\lambda t}$$

3.7.1 Linking the formula to half life

After a time, t=$T_{\frac{1}{2}}$ the fraction remaining is 0.5.

$$0.5 = e^{-\lambda t}$$

$$ln(2) = \lambda t$$

$$t = \frac{\ln(2)}{\lambda}$$

λt is a "Pure Number". As long as the same units are used for both, you can use any unit of time.

λ is the fraction of nuclei decaying per unit time or the probability of an individual nucleus decaying per second.
As N is proportional to Activity, Mass and Count Rate N can be replaced with any of these in the formula.

4 Nuclear radius

4.1 High energy electron diffraction

When a beam of high energy electrons is directed at a thin solid sample of an element they are diffracted by the nuclei of the atoms.
The electrons are diffracted by the nuclei because of their de Broglie wavelength, this is approximately equal to the radius of the nuclei. The detector measures the number of electrons per second at different angles.
The scattering of the beam of electrons occurs due to the charge, this causes intensity to decrease as angle increases.
The minimum on the graph can then be used to find the radius of the nucleus.

4.2 Dependence of nuclear radius on nucleon number

It can be shown that radius depends on mass according to:

$$R = r_0 A^{\frac{1}{3}}$$

Where r_0 is the constant 1.05fm

The graph of $\ln(R)$ against $\ln(A)$ gives a line with gradient $\frac{1}{3}$ and y intercept equal to $\ln(r_0)$

The graph of R against $A^{\frac{1}{3}}$ gives a straight line through the origin with gradient r_0

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi(r_0 A^{\frac{1}{3}})^3 = \frac{4}{3}\pi r_0^3 A$$

As Density = $\frac{\text{Mass}}{\text{Volume}}$

$$\text{Density} = \frac{Au}{\frac{4}{3}\pi r_0^3 A} = \frac{1u}{4\pi r_0^3} = \frac{1.661 \times 10^{-27}}{\frac{4}{3}\pi(1.05 \times 10^{-15})^3} = 3.4 \times 10^{17} kgm^{-3}$$

5 Radioactive isotopes in use

5.1 Radioactive dating

5.1.1 Carbon dating

Carbon-14 is used for carbon dating, this has a half life of 5570 years, meaning that there is very little decay while a plant is alive. However once the tree has died, the percentage of carbon-14 reduces as it decays. Because activity is proportional to the number of atoms still to decay, measuring the activity of the dead sample allows its age to be calculated.

5.1.1.1 Example

A sample of dead wood is found to have an activity of 0.28Bq. An equal mass of living wood is found to have an activity of 1.3Bq.Calculate the age of the sample

The half life of carbon-14 is 5570 years

Calculate the half life in seconds

$$T_{\frac{1}{2}} = 5570 \times 365 \times 24 \times 3600 = 1.76 \times 10^{11} s$$

Calculate the decay constant using the formula on the formula sheet

$$\lambda = \frac{\ln(2)}{1.76 \times 10^{11}}$$

Use the formula $A = A_0 e^{-\lambda t}$

$$0.28 = 1.8e^{-\lambda t}$$

Rearrange to find λt

$$e^{-\lambda t} = \frac{0.280}{1.30} = 0.215$$
$$\lambda t = 1.535$$

Rearrange and substitute in λ to find t

$$t = \frac{1.535}{\lambda} = \frac{1.535}{3.96 \times 10^{-12}} = 3.88 \times 10^{11} s = 12300 \text{ years}$$

5.1.2 Argon dating

$${}^{40}_{19}K + {}^{0}_{-1} e \rightarrow {}^{40}_{18} Ar + \nu_e$$

The effective half-life of the decay of ${}^{40}_{19}K$ is 1250 million years. The age of the rock can be calculated by measuring the proportion of argon-40 to potassium-40.

${}^{40}_{19}K$ also decays to ${}^{40}_{20}Ca$. This process is eight times more probable than electron capture. This means that if there was one argon atom for every N potassium atoms, there would originally be N+9 potassium atoms, eight decaying to Calcium and one decaying to argon.

5.1.2.1 Example

Suppose for every 4 potassium-40 atoms present a certain rock now mas 1 argon-40 atom, what is the age of the sample?

Find the values of N and N_0

$$N = 4 \qquad N_0 = 4 + 9 = 13$$

Substitute these values into $N = N_0 e^{-\lambda t}$

$$4 - 13e^{-\lambda t}$$

Rearrange to find t

$$t = \frac{-\ln \frac{4}{13}}{\lambda}$$

Substitute $\frac{\ln(2)}{T_{\frac{1}{2}}}$ for λ

$$t = \frac{-\ln(\frac{4}{13})}{0.693} T_{\frac{1}{2}}$$

Substitute in the known value of the half life of potassium

$$1.7 \times T_{\frac{1}{2}} = 2120 \text{ million years}$$

5.2 Radioactive tracers

A radioactive tracer follows the path of a substance through a system. These should:

- Have a half life stable enough for the necessary measurements to be made and short enough to decay quickly after use
- Emit β radiation of γ radiation so it can be detected outside the flow path

5.3 Industrial uses

5.3.1 Engine wear

The rate of wear of a piston ring can be measured by fitting a ring that is radioactive. This causes transfer of radioactive atoms from the ring to the engine oil, which can then be measured

5.3.2 Underground pipe leaks

Radioactive tracer is injected in the flow, A detector at the surface measures the leakage

5.3.3 Investigating the uptake of fertilisers by plants

The fertiliser is a β^- emitter and so can be measured in the leaves.

5.3.4 Thickness monitoring

The thickness of continuous materials can be measured by placing a β emitter and detector on either side of the material. This allows materials such as foil to have a uniform thickness.

5.3.5 Power sources for remote devices

Satellites, weather sensors etc can be powered using a radioactive isotope in a thermally insulated sealed container which absorbs all the radiation emitted by the isotope. A thermocouple attached to the container produces electricity of the container being warm.