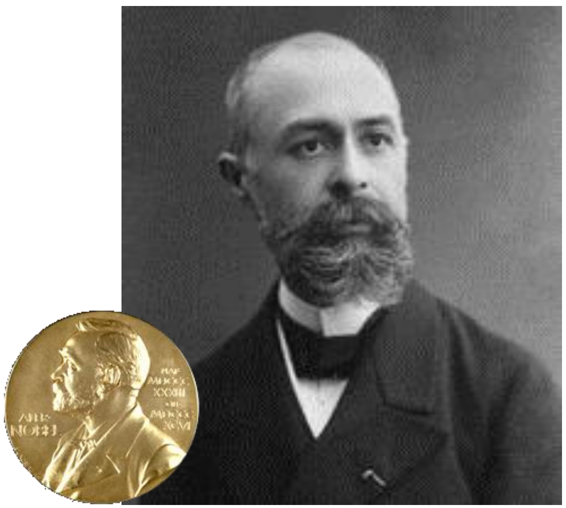
Atomic and Nuclear Physics

Topic 7.2 Radioactivity

Radioactivity

- In 1896, Henri Becquerel discovered, almost by accident, that uranium can blacken a photographic plate, even in the dark.
- Uranium emits very energetic radiation - it is radioactive.



Henri Becquerel (1852-1908)

In 1903, he shared the Nobel Prize in Physics with Pierre and Marie Curie "in recognition of the extraordinary services he has rendered by his discovery of spontaneous radioactivity".

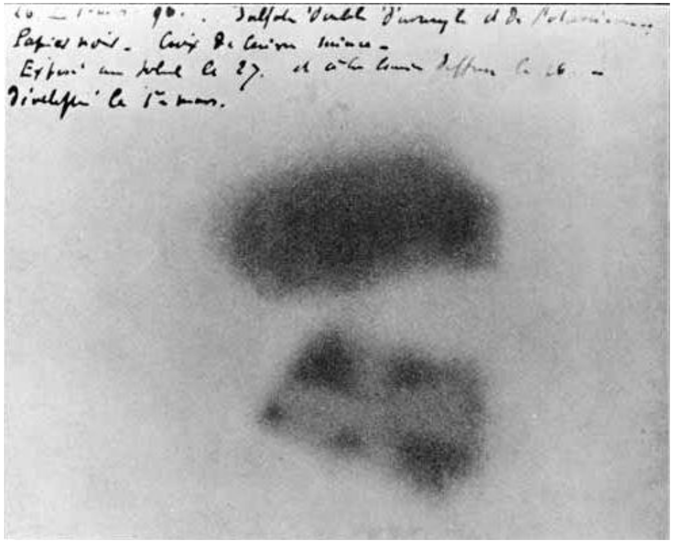


Image of Becquerel's photographic plate which has been fogged by exposure to radiation from a uranium salt.

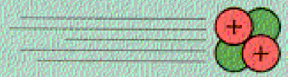
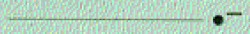
Radioactivity

- Then Marie and Pierre Curie discovered more radioactive elements including polonium and radium.
- Scientists soon realised that there were three different types of radiation.
- These were called alpha (α), beta (β), and gamma (γ) rays from the first three letters of the Greek alphabet.

Marie Curie (1867-1934)

Pierre Curie (1859-1906)

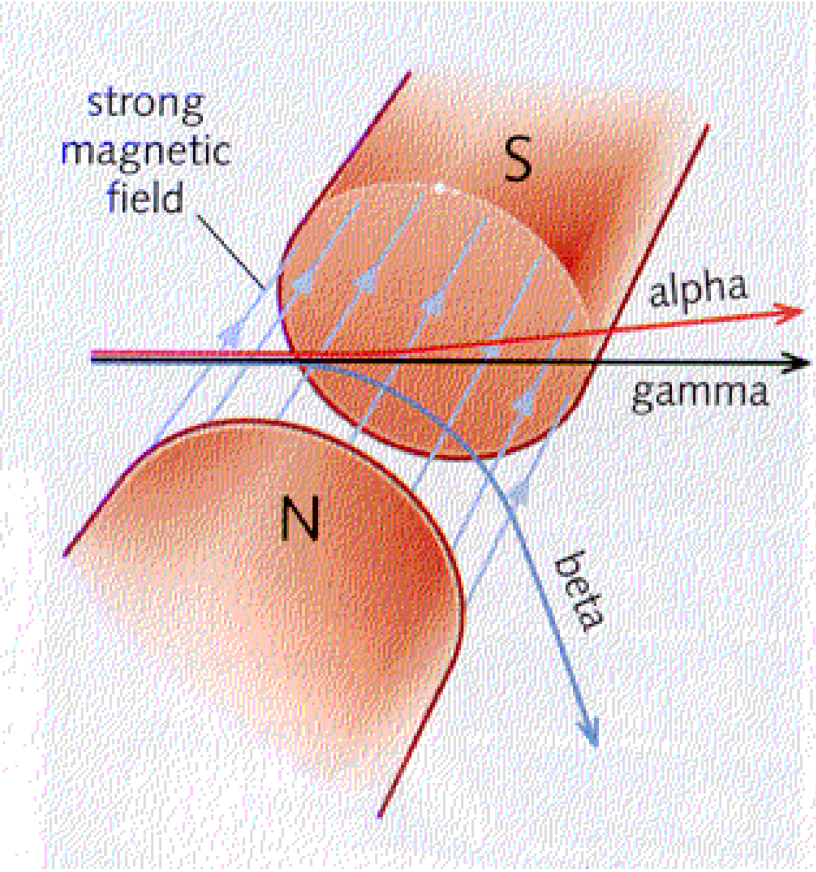
Properties of Alpha, Beta and Gamma Radiation

type of radiation	alpha particles (α)	beta particles (β)	gamma rays (γ)
	 each particle is 2 protons + 2 neutrons (it is identical to a nucleus of helium-4)	 each particle is an electron (created when the nucleus decays)	 electromagnetic waves similar to X-rays
relative charge compared with charge on proton	+2	-1	0
mass	high, compared with betas	low	–
speed	up to 0.1 × speed of light	up to 0.9 x speed of light	speed of light
ionizing effect	strong	weak	very weak
penetrating effect	not very penetrating: stopped by a thick sheet of paper, or by skin, or by a few centimetres of air	penetrating, but stopped by a few millimetres of aluminium or other metal	very penetrating: never completely stopped, though lead and thick concrete will reduce intensity
effects of fields	deflected by magnetic and electric fields	deflected by magnetic and electric fields	not deflected by magnetic or electric fields

Properties of Alpha, Beta and Gamma Radiation

The diagram shows how the different types are affected by a magnetic field.

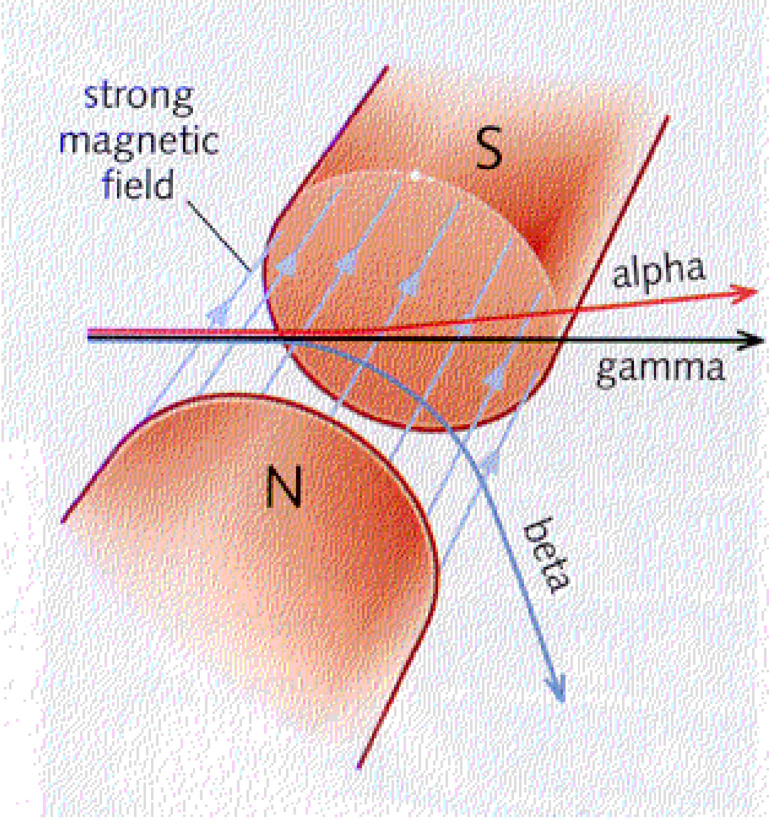
- The alpha beam is a flow of positively (+) charged particles, so it is equivalent to an electric current.
- It is deflected in a direction given by Fleming's left-hand rule - the rule used for working out the direction of the force on a current-carrying wire in a magnetic field.



Properties of Alpha, Beta and Gamma Radiation

- The beta particles are much lighter than the alpha particles and have a negative (-) charge, so they are deflected more, and in the opposite direction.

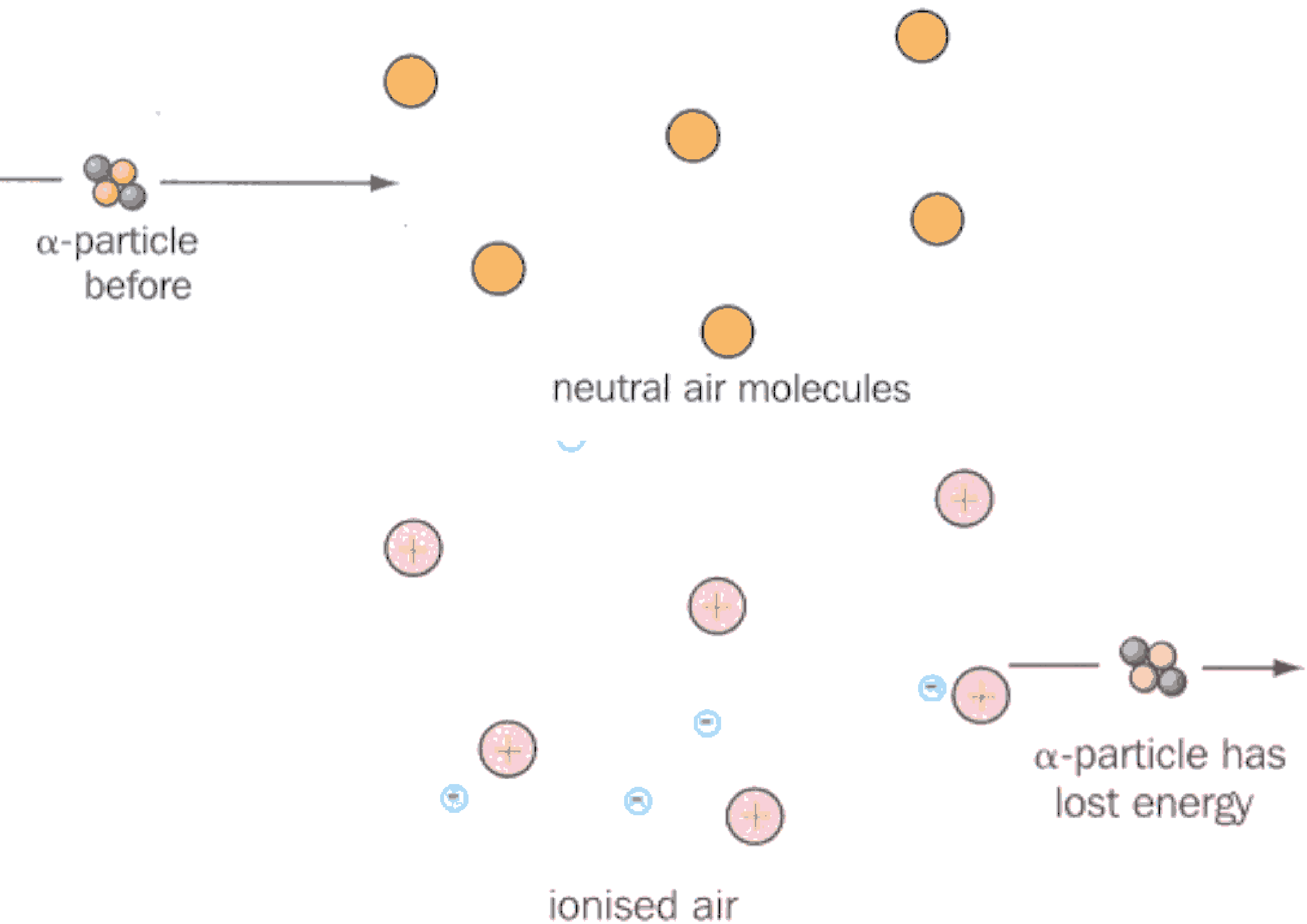
- Being uncharged, the gamma rays are not deflected by the field.
- Alpha and beta particles are also affected by an electric field - in other words, there is a force on them if they pass between oppositely charged plates.



Ionising Properties

- α -particles, β -particles and γ -ray photons are all very energetic particles.
- We often measure their energy in electron-volts (eV) rather than joules.
- Typically the kinetic energy of an α -particle is about 6 million eV (6 MeV).
- We know that radiation ionises molecules by `knocking' electrons off them.
- As it does so, energy is transferred from the radiation to the material.
- The next diagrams show what happens to an α-particle

Ionising Properties



Penetrating power of alpha radiation.

- Since the α-**particle** is a heavy, relatively slow-moving particle with a charge of +2e, it interacts strongly with matter.

- It produces about 1×10^5 ion pairs per cm of its path in air.

- After passing through just a few cm of air it has lost its energy.

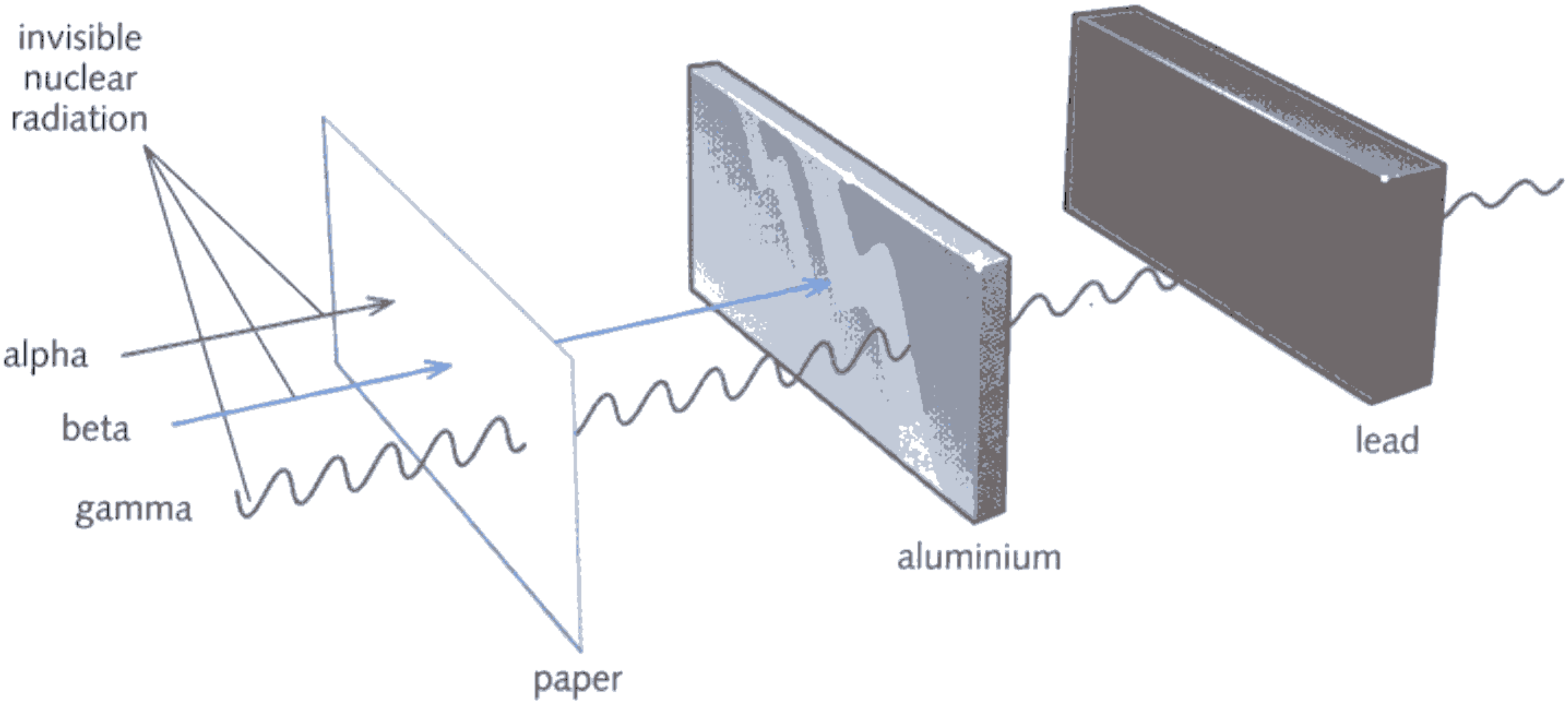
Penetrating power of beta radiation.

- The β**-particle** is a much lighter particle than the α -particle and it travels much faster.
- Since it spends just a short time in the vicinity of each air molecule and has a charge of only -le, it causes less intense ionisation than the α -particle.
- The β -particle produces about 1×10^3 ion pairs per cm in air, and so it travels about 1 m before it is absorbed.

Penetrating power of gamma radiation.

- A γ**-ray photon** interacts weakly with matter because it is uncharged and therefore it is difficult to stop.
- A γ -ray photon often loses all its energy in one event.
- However, the chance of such an event is small and on average a γ -photon travels a long way before it is absorbed.

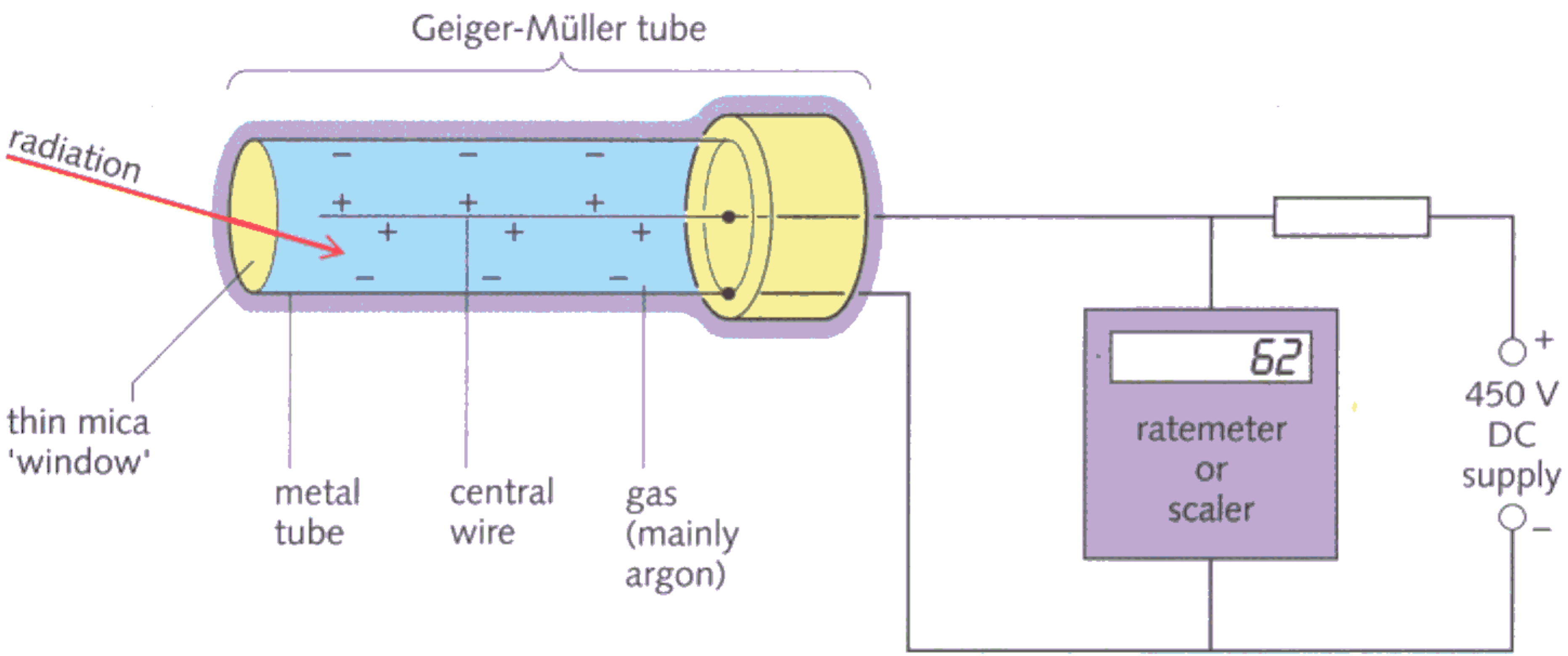
Alpha, Beta and Gamma Radiation



Detection of alpha radiation.

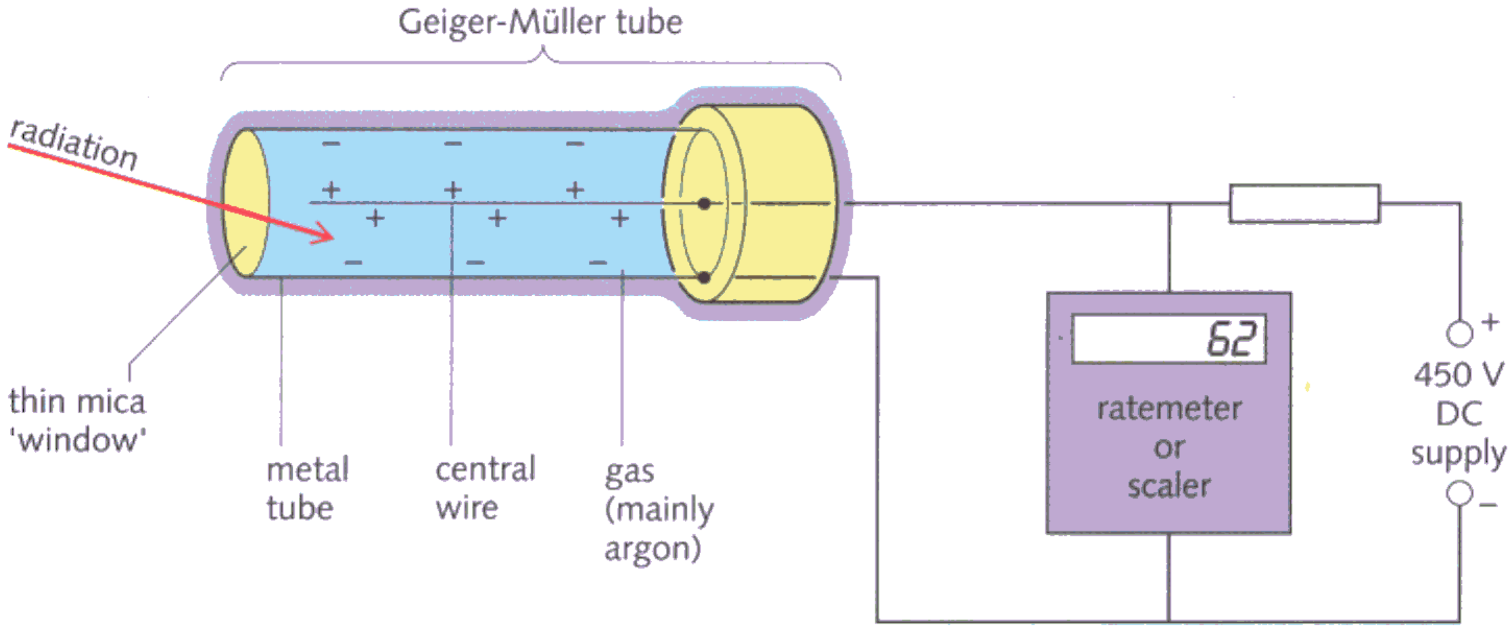
Geiger-Müller (GM) tube

- This can be used to detect alpha, beta, and gamma radiation.



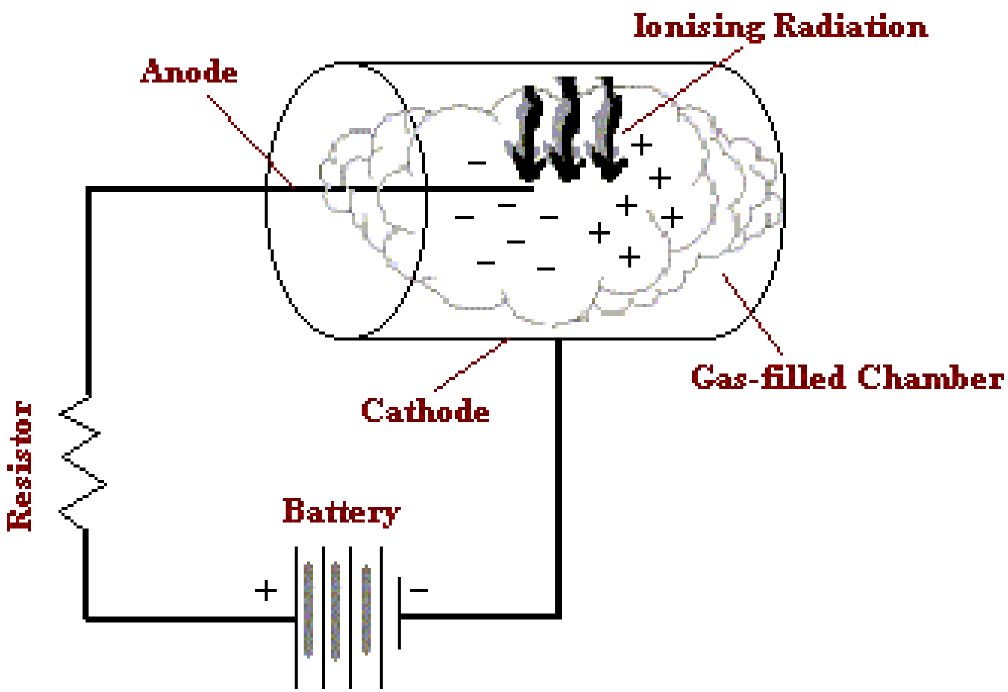
Geiger-Muller (GM) tube

- The `window' at the end is thin enough for alpha particles to pass through.
- If an alpha particle enters the tube, it ionizes the gas inside.
- This sets off a high-voltage spark across the gas and a pulse of current in the circuit.
- A beta particle or burst of gamma radiation has the same effect.



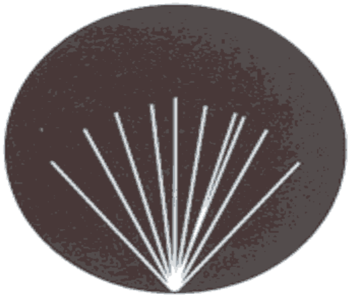
Ionisation Chamber

- The ionisation chamber is another detector which uses the ionising power of radiation.
- The chamber contains fixed electrodes, which attract electrons and ions produced by the passage through the chamber of high-speed particles or rays.
- When the electrodes detect ions or electrons, a circuit is activated and a pulse is sent to a recording device such as a light.

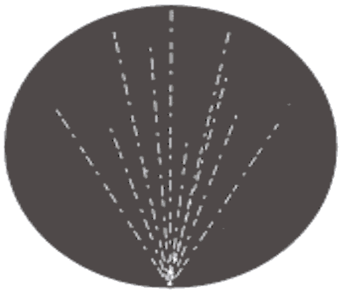


Cloud and Bubble Chamber

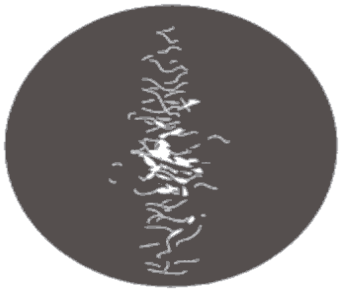
- Have you looked at the sky and seen a cloud trail behind a high flying aircraft?
- Water vapour in the air condenses on the ionised exhaust gases from the engine to form droplets that reveal the path of the plane.
- A cloud chamber produces a similar effect using alcohol vapour.
- Radiation from a radioactive source ionises the cold air inside the chamber.
- Alcohol condenses on the ions of air to form a trail of tiny white droplets along the path of the radiation.
- The diagrams below show some typical tracks



α-radiation



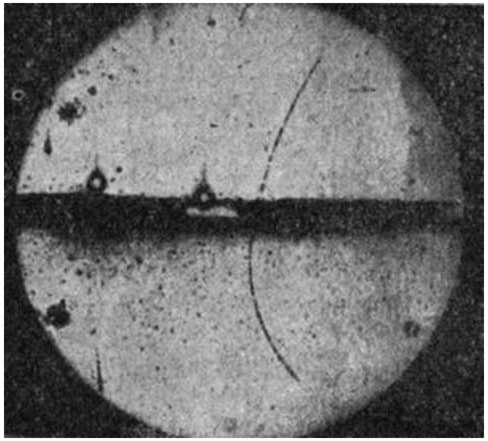
high-energy β-radiation



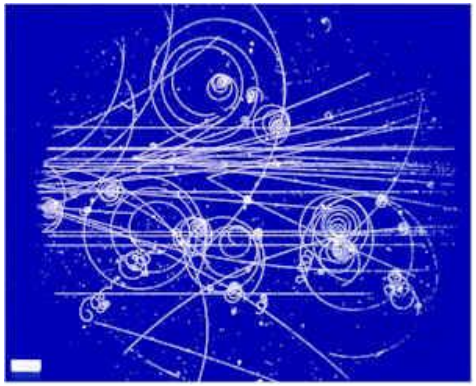
γ-radiation

Cloud and Bubble Chamber

- The α-radiation produces dense straight tracks showing intense ionisation.
- Notice that all the tracks are similar in length.
- The high-energy β-ray tracks are thinner and less intense.

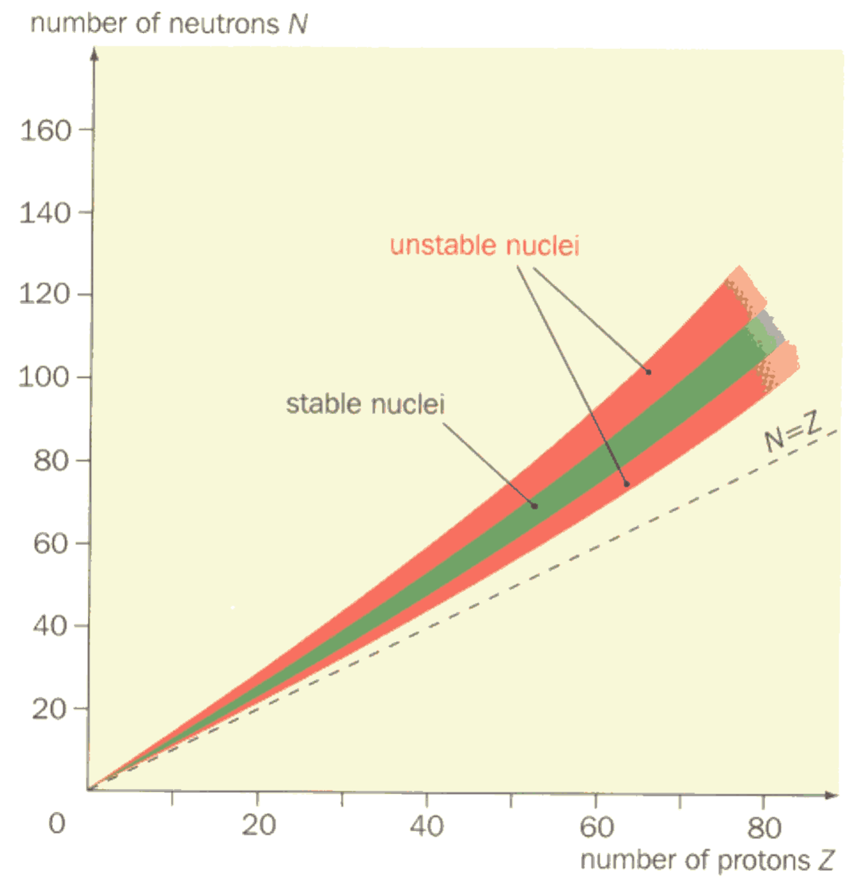


- The tracks vary in length and most of the tracks are much longer than the α -particle tracks.
- The γ-rays do not produce continuous tracks.
- A bubble chamber also shows the tracks of ionising radiation. The radiation leaves a trail of vapour bubbles in a liquid (often liquid hydrogen).



Stability

- If you plot the neutron number N against the proton number Z for all the known nuclides, you get the diagram shown here
- Can you see that the stable nuclides of the lighter elements have approximately equal numbers of protons and neutrons?
- However, as Z increases the `stability line' curves upwards.
- Heavier nuclei need more and more neutrons to be stable.



Can we explain why?

A plot of neutron number versus proton number is also called Segre plot.

Stability

- It is the strong nuclear force that holds the nucleons together, but this is a very short range force.
- The repulsive electric force between the protons is a longer range force.
- So in a large nucleus all the protons repel each other, but each nucleon attracts only its nearest neighbours.
- More neutrons are needed to hold the nucleus together (although adding too many neutrons can also cause instability).
- There is an upper limit to the size of a stable nucleus, because all the nuclides with $Z > 83$ are unstable.

Radioactive decay equations

Alpha decay

- An alpha-particle is a helium nucleus and is written $^4_2\mathrm{He}$ or $^4_2\alpha$
- It consists of 2 protons and 2 neutrons.
- When an unstable nucleus decays by emitting an α -particle
- it loses 4 nucleons and so **its nucleon number decreases by 4.**
- Also, since it loses 2 protons, **its proton number decreases by 2**
- The nuclear equation is

$$^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + {}^4_2\alpha$$

Note that the top numbers balance on each side of the equation. So do the bottom numbers.

Beta decay

- Many radioactive nuclides decay by β-emission.
- This is the emission of an electron *from the nucleus.*
- But there are no electrons in the nucleus!

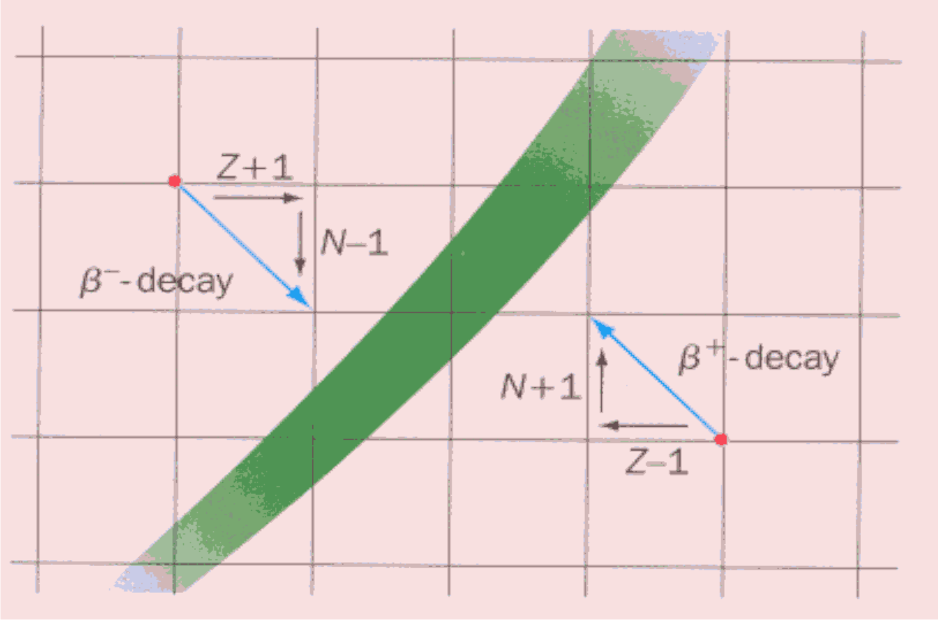
- What happens is that one of the neutrons changes into a proton (which stays in the nucleus) *and* an electron (which is emitted as a β-particle).
- This means that **the proton number increases by 1,** while the total **nucleon number remains the same.**
- The nuclear equation is

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e $$

Notice again, the top numbers balance, as do the bottom ones.

Beta decay

- A radio-nuclide *above* the stability line decays by β-emission.
- Because it loses a neutron and gains a proton, it moves diagonally *towards* the stability line, as shown on this graph.



Gamma decay

- Gamma-emission does not change the structure of the nucleus, but it does make the nucleus more stable because it reduces the energy of the nucleus.

Decay chains

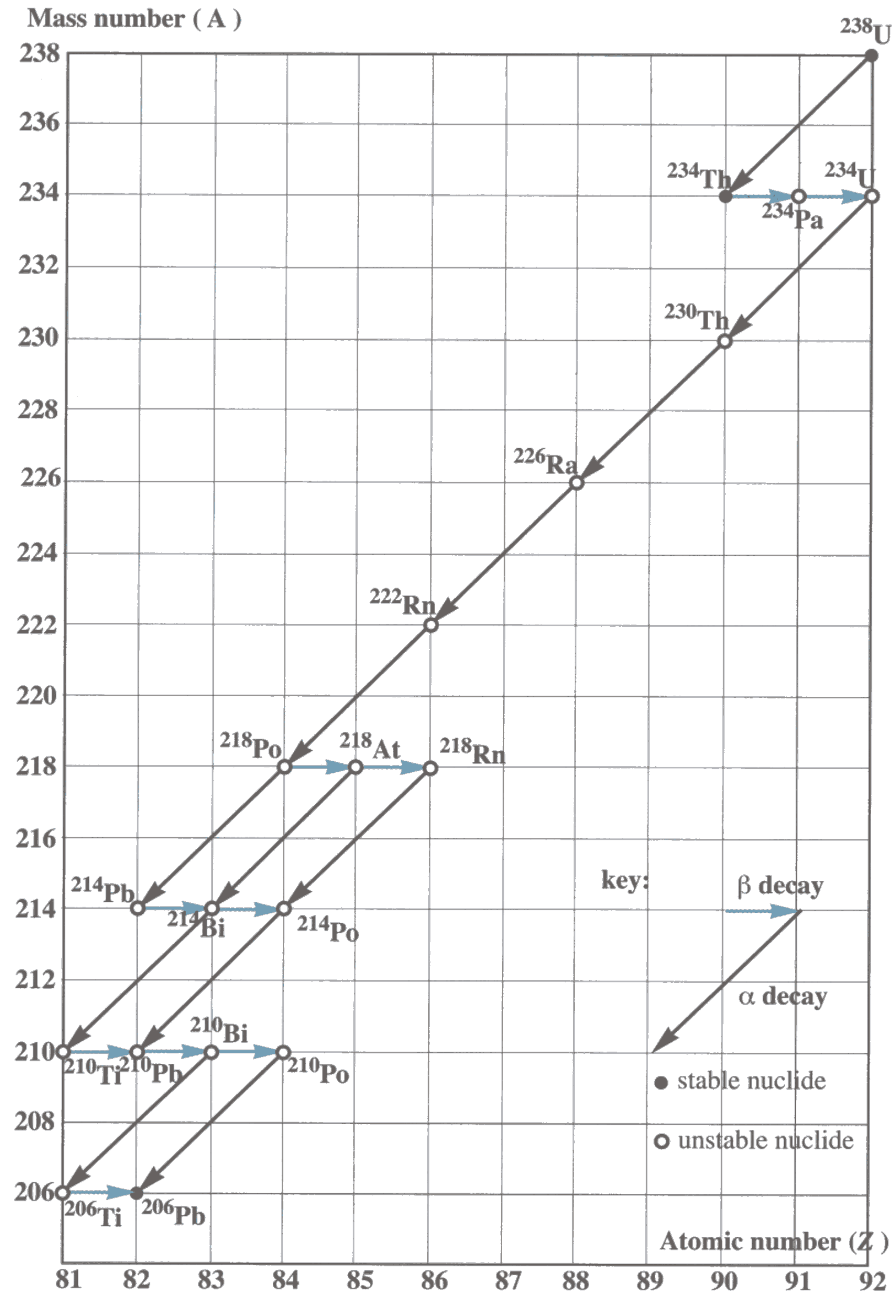
- A radio-nuclide often produces an unstable daughter nuclide.
- The daughter will also decay, and the process will continue until finally a stable nuclide is formed.
- This is called a decay chain or a decay series.
- Part of one decay chain is shown below

$$^{238}_{92}U \xrightarrow{\alpha} {}^{234}_{90}Th \xrightarrow{\beta} {}^{234}_{91}Pa \xrightarrow{\beta} {}^{234}_{92}U \xrightarrow{\alpha} {}^{230}_{90}Th \xrightarrow{\alpha} {}^{226}_{88}Ra$$

Decay chains

- When determining the products of decay series, the same rules apply as in determining the products of alpha and beta, or artificial transmutation.

- The only difference is several steps are involved instead of just one.



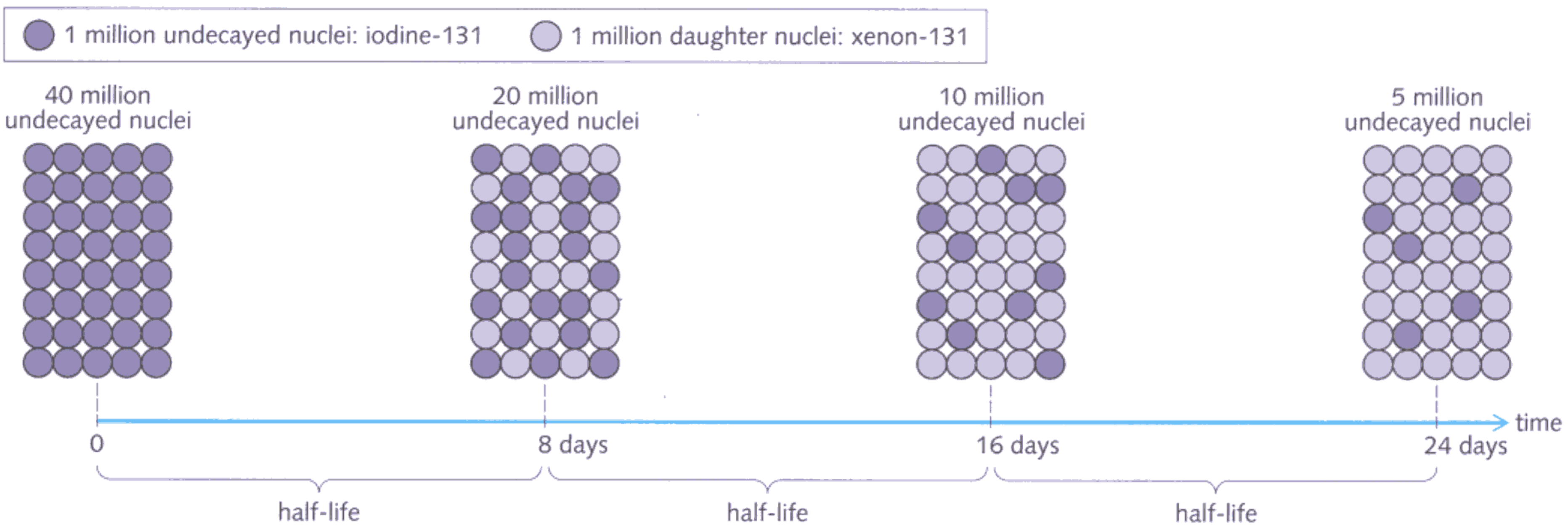
Half-life

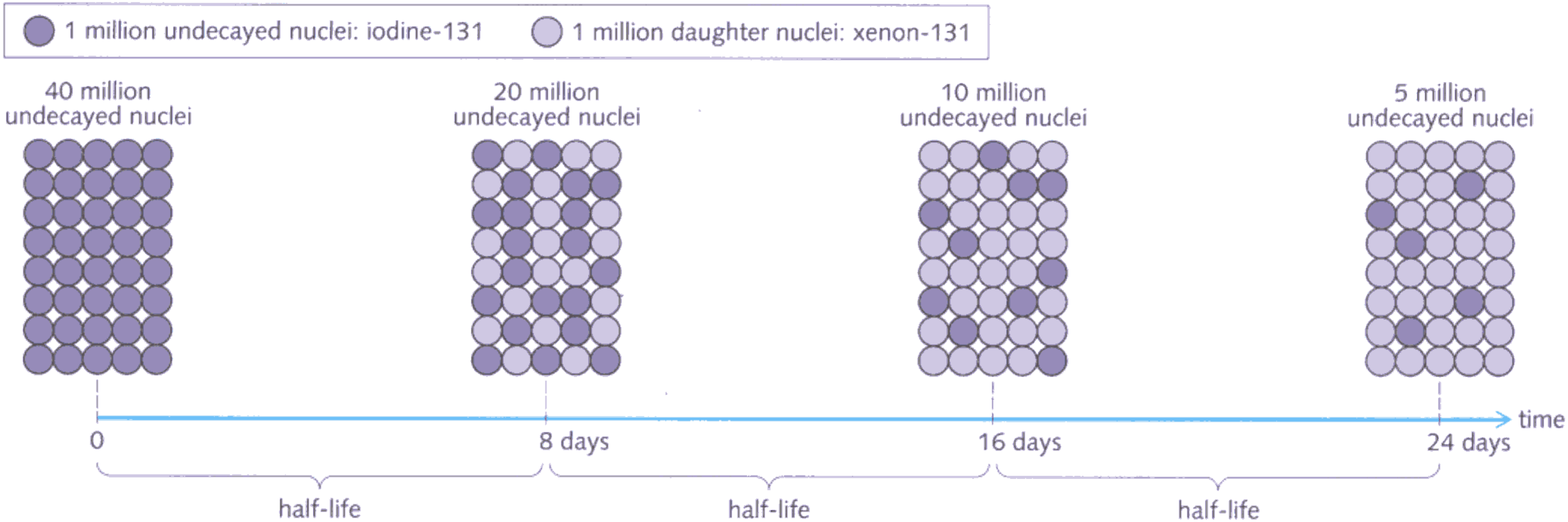
- Suppose you have a sample of 100 identical nuclei.
- All the nuclei are equally likely to decay, but you can never predict which individual nucleus will be the next to decay.
- The decay process is completely **random.**
- Also, there is nothing you can do to `persuade' one nucleus to decay at a certain time.
- The decay process is **spontaneous.**

- Does this mean that we can never know the rate of decay?
- No, because for any particular radio-nuclide there is a certain **probability** that an individual nucleus will decay.
- This means that if we start with a large number of identical nuclei we can predict how many will decay in a certain time interval.

Half-life

- Iodine-131 is a radioactive isotope of iodine.
- The chart illustrates the decay of a sample of iodine-131.
- On average, 1 nucleus disintegrates every second for every 1000 000 nuclei present.





To begin with, there are 40 million undecayed nuclei.

8 days later, half of these have disintegrated.

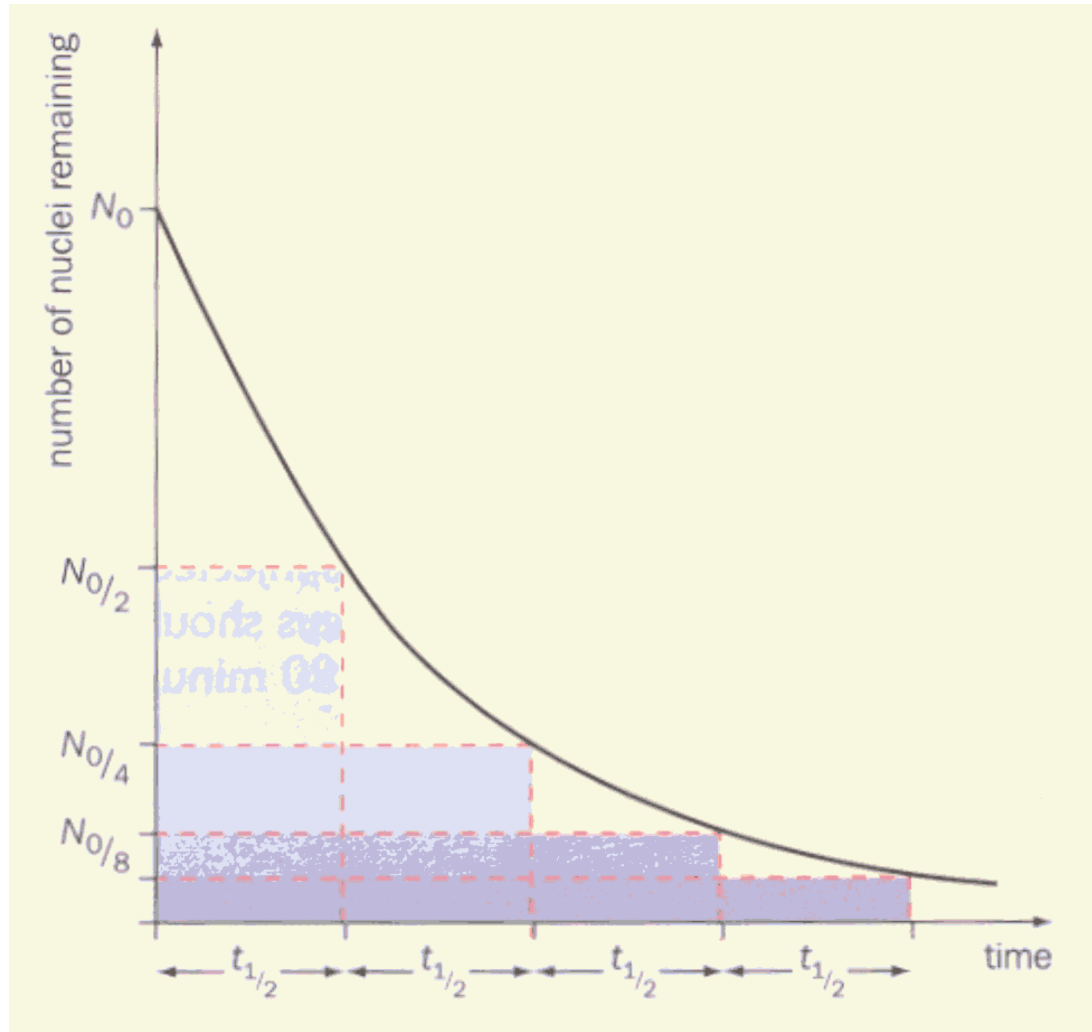
With the number of undecayed nuclei now halved, the number of disintegrations over the next 8 days is also halved.

It halves again over the next 8 days... and so on.

Iodine-131 has a **half-life** of 8 days.

Half-life

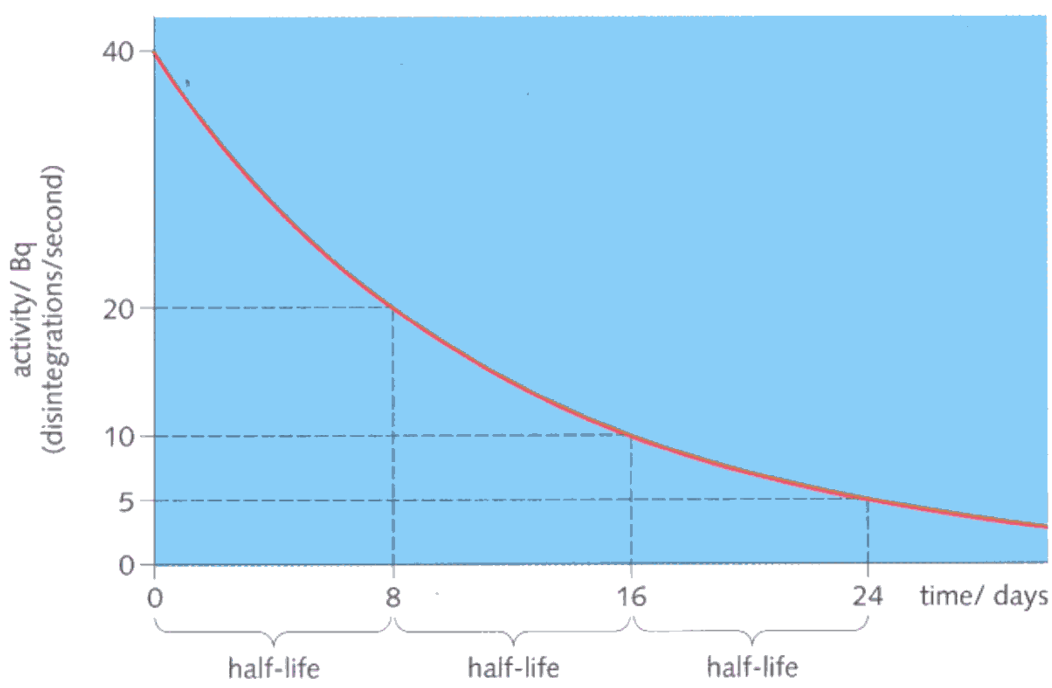
- The half-life of a radioactive isotope is the time taken for half the nuclei present in any given sample to decay.



Activity and Half-life

- In a radioactive sample, the average number of disintegrations per second is **called the activity.**
- The SI unit of activity is the **becquerel (Bq).**
- An activity of, say, 100 Bq means that 100 nuclei are disintegrating per second.

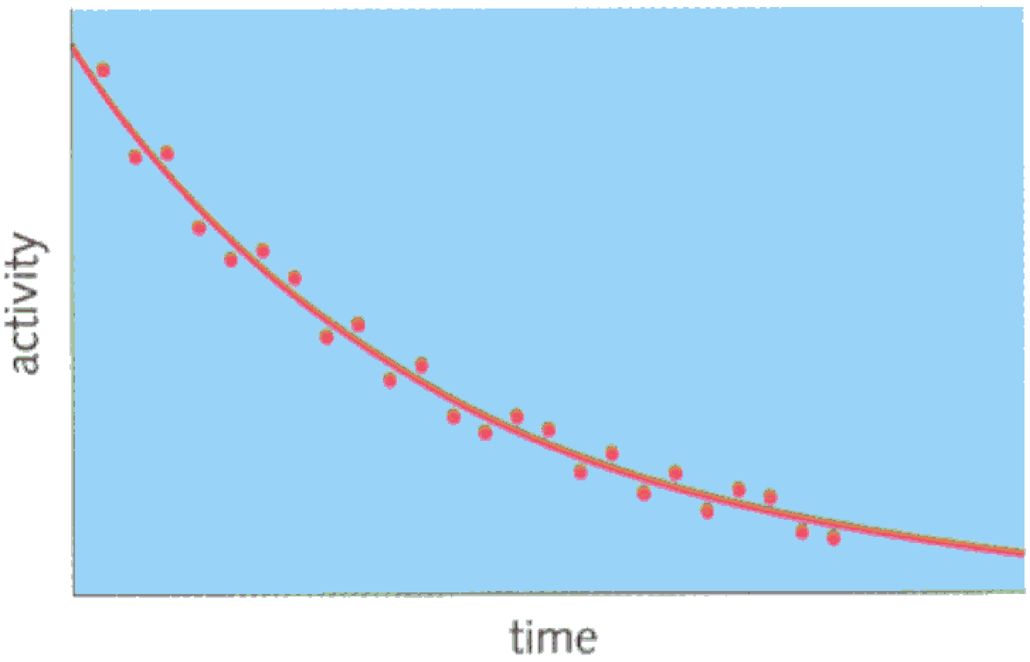
- The graph shows how, on average, the activity of a sample of iodine-131 varies with time.
- As the activity is always proportional to the number of undecayed nuclei, it too halves every 8 days.



Activity and Half-life

- So `half-life' has another meaning as well:

  The half-life of a radioactive isotope is the time taken for the activity of any given sample to fall to half its original value.



▲ Radioactive decay is a random process. So, in practice, the curve is a 'best fit' of points which vary irregularly like this.

Exponential Decay

- Any quantity that reduces by the same fraction in the same period of time is called an exponential decay curve.
- The half life can be calculated from decay curves
- Take several values and then take an average