A2 Level Physics

Chapter 10 Nuclear Radiation

10.1.1 Radioactivity

Notes

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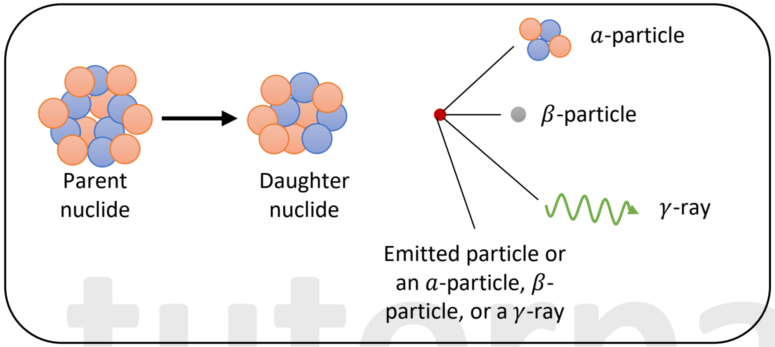
Radioactivity Decay

An unstable atomic nucleus will 'break down' in order to become more stable.

Radioactive decay occurs when the nucleus decays spontaneously, losing energy and/or particles until it reaches a stable state. Individual radioactive decay is random and unpredictable.



When one type of atom, known as the PARENT nuclide, decays or disintegrates, it transforms into another type of atom, known as the DAUGHTER nuclide.

There are four types of radiation emitted by radioactive materials:

1) Alpha (α)-particle

2) Beta-minus (β^-)-particle

3) Beta-plus (β^+)-particle

4) Gamma (γ)-rays

Basic Characteristics of the 3 types of nuclear radiation

- An α-particle is a helium nucleus made up of 2p + 2n. It is a relatively large, positively charged, particle of matter.
- A β^--particle is a high speed (high energy) electron. It is an extremely light, negatively charged, particle of matter.
- A β^+-particle is a high speed (high energy) positron (a positive electron). It's an extremely light, positively charged, particle of matter.
- A γ-ray is a high energy photon of electromagnetic radiation with a short wavelength and a high frequency.

Radiation	Symbol	Constituent	Mass (u)	Charge
Alpha	${}^4_2\alpha$ or ${}^4_2He$	A helium nucleus – 2 protons and 2 neutrons	4	+2
Beta-minus	β^-	Electron	(negligible)	-1
Beta-plus	β^+	Positron (a positive electron)	(negligible)	+1
Gamma	γ	Short-wavelength, high-frequency electromagnetic wave.	0	0

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Nuclear Decay Equations

1) Alpha (α)-decay

When an unstable nucleus decays by emitting an α-particle (i.e. a helium nucleus) it loses 2 protons + 2 neutrons, reducing its atomic number (A) by 4 and its proton number (Z) by 2.

Only very large atoms (with more than 82 protons), such as Uranium, experience alpha decay. The strong nuclear force cannot keep these atoms stable because their nuclei are too big. In order to make themselves more stable, they release an alpha particle, from the nucleus.

The nuclear equation that describes the decay of a parent nuclide into a daughter nuclide by α-particle emission is:

$$^{A}_{Z}X \rightarrow \, ^{A-4}_{Z-2}Y + \, ^{4}_{2}He + (Energy)$$

Parent nuclide | Daughter nuclide | α-particle | Appears as K.E. of daughter and α-particle

Throughout the equation, A and Z are balanced (i.e. there is mass and charge conservation).

Example

If Uranium – 235 emits an α-particle, it decays into Thorium – 231.

This a-decay has the following equation:

$$^{235}_{92}U \rightarrow \, ^{231}_{90}Th + \, ^{4}_{2}He + (Energy)$$

A and Z are balanced throughout the equation and mass and charge are conserved.

Nuclear Decay Equations

2) Beta Minus (β^-, e^-)-decay

When an unstable atom decays by releasing a β^-- particle (i.e. a high speed electron), one of the neutrons in the nucleus transforms into a proton (which remains in the nucleus) plus an electron (which is emitted as a β^- - particle) plus another particle, called an antineutrino.

Isotopes that are “neutron rich” (i.e. have too many neutrons compared to protons in their nucleus) undergo beta decay. When a nucleus ejects a beta particle, one of the neutrons in the nucleus is converted to a proton. Therefore the proton number increases by one, while the nucleon number remains the same.

The nuclear equation that describes the decay of a parent nuclide into a daughter nuclide by β^- - particle emission is:

$$^{A}_{Z}X \rightarrow \, _{Z+1}^{A}Y + \, _{-1}^{0}e + \, _{0}^{0}\overline{v} + (Energy)$$

Parent nuclide | Daughter nuclide | β^- - particle | Antineutrino

Throughout the equation, A and Z are balanced (i.e. there is mass and charge conservation).

Example

If Carbon – 14 emits an β^- - particle, it decays into Nitrogen – 14 and releases an antineutrino.

This β-decay has the following equation:

$$^{14}_{6}C \rightarrow \, ^{14}_{7}N + \, _{-1}^{0}e + \, _{0}^{0}\overline{v} + (Energy)$$

A and Z are balanced throughout the equation and mass and charge are conserved.

Nuclear Decay Equations

3) Beta Plus (β^+, e^+)-decay

When an unstable atom decays by emitting a β^+ - particle [i.e. a positron (the opposite of an electron)], one of the protons in the nucleus changes into a neutron (which remains in the nucleus) plus a positron (which is released as a β^+ - particle) plus another particle, called a neutrino.

The nuclear equation that describes the decay of a parent nuclide into a daughter nuclide by β^+ - particle emission is:

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

Parent nuclide | Daughter nuclide | β^+ - particle | Neutrino

Throughout the equation, A and Z are balanced (i.e. there is mass and charge conservation).

Example:

If Polonium-15 emits an β^+ - particle, it decays into Silicon-14 and releases a neutrino.

The equation for this a-decay can be seen below:

$$^{30}_{15}Po \rightarrow {}^{30}_{14}Si + {}^{0}_{+1}e + {}^{0}_{0}v + (Energy)$$

A and Z are balanced throughout the equation and mass and charge are conserved.

Nuclear Decay Equation

4) Gamma (γ) Decay

Nuclear reactions typically result in the production of gamma rays. In the alpha decay of U -238, two gamma rays of varying energies are emitted in addition to the alpha particle.

The nuclear equation which shows γ emission is:

$$^{238}_{92}U \rightarrow {}^{4}_{2}He + {}^{234}_{90}Th + 2{}^{0}_{0}\gamma$$

As before A and Z are balanced across the equation and mass and charge are conserved.

Almost all nuclear reactions produce gamma rays, but they aren't shown in order to keep things simple.

We'll look at nuclear reactions in greater depth later.

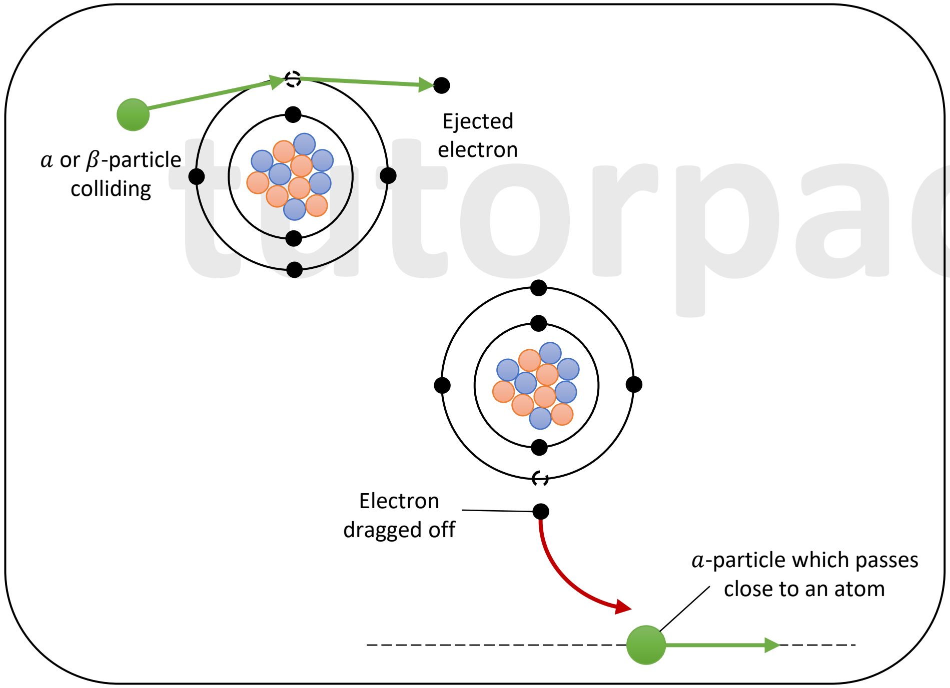
Ionisation

α and β-particle are electrically charged and move very fast.

When α or β-particles collide with atoms, one or more electrons may be knocked out of the atoms, causing the atoms to become ionised.

Also, if an α-particle passes close enough to an atom, electrostatic attraction can pull an electron away, causing ionisation.

An ionising event causes the α-particle or β-particle to lose some energy, and after many such events, the α or β will lose all of its energy and come to a halt, causing no further ionisation.

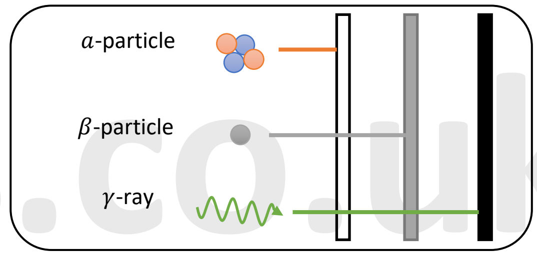


Penetration of nuclear radiation

Different types of radiation have different penetrating strengths. The more penetrating the radiation, the thicker or denser a material has to be in order to absorb it.

- Alpha – an alpha source (such as americium-241) can be absorbed by paper, skin or a few centimetres of air.
- Beta-minus – a beta source (such as strontium-90) can be absorbed by about 3 millimetres of aluminium
- Gamma – a gamma source (such as cobalt-60) can be absorbed by many centimetres of lead, or several metres of concrete.

Beta-plus particles are instantly annihilated by electrons, giving them a range of zero.



Explaining the different penetrations of the three radiations:

The a-particle interacts strongly with matter and causes intensive ionisation since it is a heavy, relatively slow-moving particle with a charge of +2e. As a result, it is stopped by a piece of paper and has lost all of its energy after travelling only a few cm in the air.

The β-particle is nearly 7000 times lighter than the a-particle and travels much faster. Since it only spends a short time in the presence of an air molecule and has a charge of only -1e, it causes less intense ionisation than the a-particle, allowing the β-particle to travel further in air. This explains its higher penetrating strength and air range of 50–100 cm.

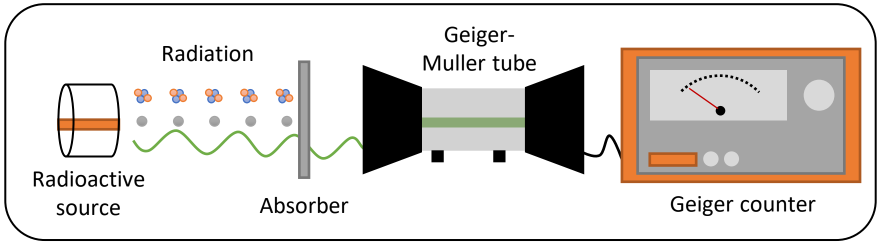
Since a γ-ray photon travels at the speed of light and has no charge, it interacts with matter very weakly and causes little ionisation. As a result, it can only be stopped by thick lead, and it can travel a long distance through air before losing all of its energy.

The Geiger-Muller (G-M) Tube

The Geiger-Muller (GM) tube is a device that detects α, β *and* γ-radiation, and is used with an amplifier and counter (called a scalar). It detects the ionisation caused by these radiations as they travel through the air.

Identifying nuclear radiation

Using the apparatus below, you can determine the type(s) of radiation released by a source by seeing if it passes through various materials.



- Remember that the count recorded by the G-M tube will be caused by the radiation from the source plus that due to background radiation. So first obtain the background radiation count several times over a one-minute period with no source present, and determine the average background count rate. Record this background radiation count rate.

- Then place an unknown source near to a G-M tube and record the count rate.

- Next, between the source and the G-M tube, place a sheet of paper and record the new count rate.

- Replace the paper with a 3mm thick sheet of aluminium and record the count rate.

- For each count rate that is recorded the actual or corrected count rate is calculated as follows:

Corrected count rate = count rate from source – background radiation count rate

You can figure out what kind of radiation the source was emitting based on when the count rate dropped dramatically. If, for example, paper has no effect and aluminium causes a large (but not total) reduction in count rate, the source must be producing beta and gamma radiation.

Effect of Electric and Magnetic Fields

Electric Field

- α-particles are positively charged and so defect towards the negative plate.

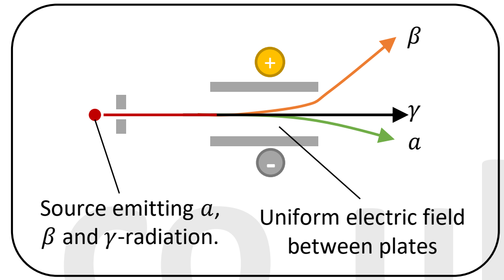
- β^--particles are negatively charged and so deflect towards the positive plate.

- β^+-particles are positively charged and so deflected towards the positive plate.

- γ-rays are uncharged and so pass through the plates without being deflected.

For a given field strength,

$$\beta\ deflection > \alpha\ deflection$$



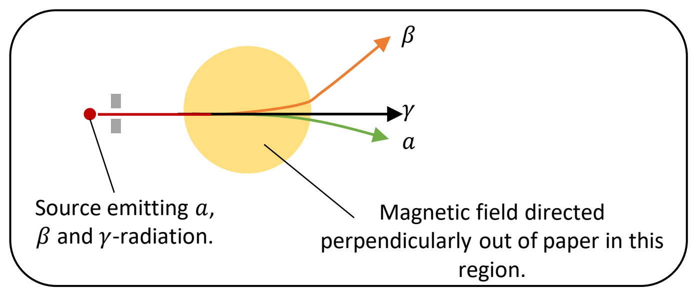
Magnetic Field

The direction of the force exerted on the moving $\alpha's$ & $\beta's$ is determined using Fleming's left-hand rule.

It worth noting that β's ($e's$) moving to the right is equivalent to conventional current moving to the left.

For a given magnetic flux density,

$$\beta\ deflection > \alpha\ deflection$$



Background Radiation

Background radiation is a type of nuclear radiation that is present everywhere and comes from a variety of sources.

No matter where you are, there is always a low level of radiation present, which is known as background radiation.

Sources of background radiation

Background radiation can come from many sources, such as:

- Cosmic radiation – cosmic rays are mostly high-energy protons that come from outer space. When they collide with particles in the upper atmosphere, nuclear radiation is produced.
- Man-made radiation – radiation from medical or industrial sources makes up a tiny, tiny proportion of the background radiation in most places.
- Living things – carbon is found in all living things, including plants and animals, and some of this carbon will be radioactive carbon-14.
- The air – radioactive radon gas is released into the air by rocks. It emits alpha radiation. The concentration of this gas in the atmosphere varies greatly from place to place, but it's usually the most significant contributor to the background radiation.
- The ground and building – nearly every rock contains radioactive materials.

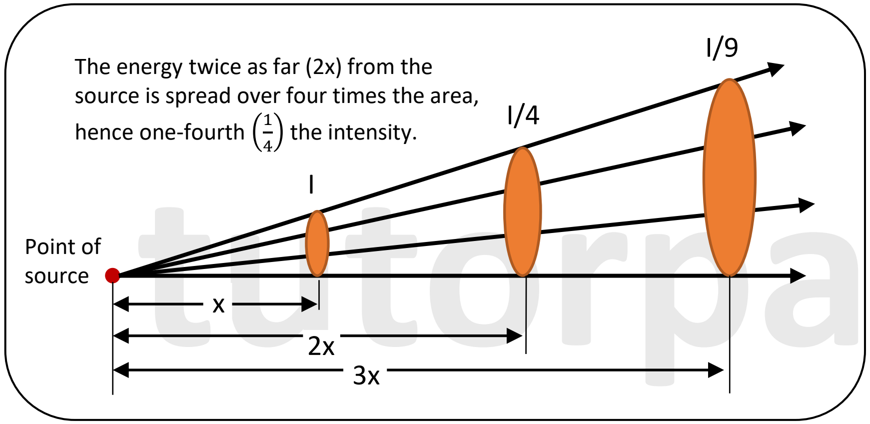
Summary of nuclear radiation properties

Radiation	Symbol	Ionising power	Speed	Penetrating power	Affected by magnetic field
Alpha	α	Strong	Slow	Absorbed by paper or a few cm of air	Yes
Beta-minus	β^-	Weak	Fast	Absorbed by approx. 3 mm of aluminium	Yes
Beta-plus	β^+	Weak	Fast	Annihilated by electron, so virtually zero range.	Yes
Gamma	γ	Very weak	Speed of light	Absorbed by many cm of lead, or several m of concrete	No

Inverse-Square Law for γ radiation

Gamma radiation is emitted in all directions by a gamma source. As you travel further away from the source, the radiation spreads out. The amount of radiation per unit area is called the intensity of radiation, and it decreases as you travel further away from the source.

When you measure the intensity, I, at a distance, x, from the source you'll notice that the intensity decreases by the square of the distance from the source.



This can be written as the equation:

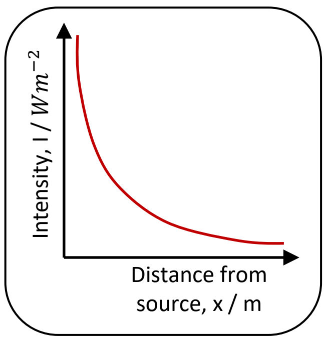
$$I = \frac{k}{x^2}$$

Where:

I = intensity, Wm^{-2}

k = constant of proportionality, W

x = distance from source, m



A graph of how intensity varies with distance from a source.

Inverse-Square Law for γ radiation

Worked Example

Radiation coming from a gamma source at a distance 0.55 m had an intensity of $3.0 \times 10^{-10}\ Wm^{-2}$. At 1.5 m from the source, what intensity would be recorded?

Intensity at 0.50 m $\Longrightarrow I = \frac{k}{x^2} \Rightarrow 3.0 \times 10^{-10} = \frac{k}{0.55^2}$

Therefore $k = 3.0 \times 10^{-10} \times 0.55^2 = 9.075 \times 10^{-11}$

So intensity at $1.5m \Longrightarrow I = \frac{9.075 \times 10^{-11}}{1.5^2} = 4.03 \times 10^{-11} Wm^{-2}\ (2d.p.)$

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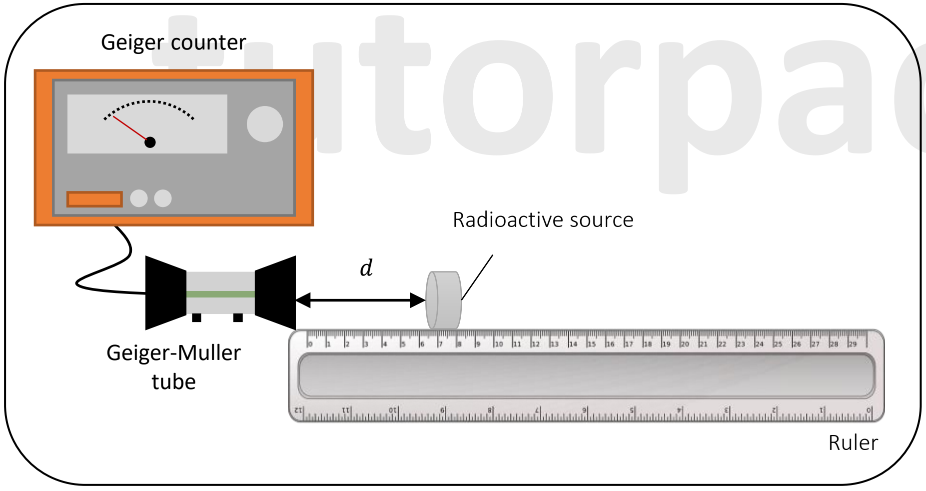
Experimental verification of Inverse-Square Law for Gamma Radiation (AQA Only)

This inverse-square law can be demonstrated by using a Geiger counter to detect intensity at various distances from a gamma source, as illustrated below:

Apparatus:

- Geiger-Muller tube
- Geiger counter
- Ruler
- Radioactive source



Experimental verification of Inverse-Square Law for Gamma Radiation (AQA Only)

Method:

Since the Geiger-Muller tube's collection area remains constant in this experiment, the intensity is proportional to the count rate (in counts per second) detected by the tube.

1) Set up the apparatus as shown above but without the radioactive source. The Geiger-Muller tube must be lined up with the start of the ruler.
2) Switch the Geiger counter on and record at least three readings of the background radiation count rate and calculate the average.
3) Place the radioactive source a distance d away from the tube with care.
4) Record three readings of the count rate from this distance.
5) Then record the count rate after doubling the distance between the source and the tube $(2d)$. Take three count rate readings at this distance.
6) Step 5 should be repeated for distances of $3d, 4d$, and so on….
7) Put the radioactive source away as soon as the experiment is over; you do not want to be exposed to any more radiation than necessary.
8) Calculate the average of the count rates for each distance. Subtract the average background radiation count rate from the average count rate at each distance to eliminate counts related to background radiation at each distance. Then plot a graph of the corrected count rate against tube distance from the source.

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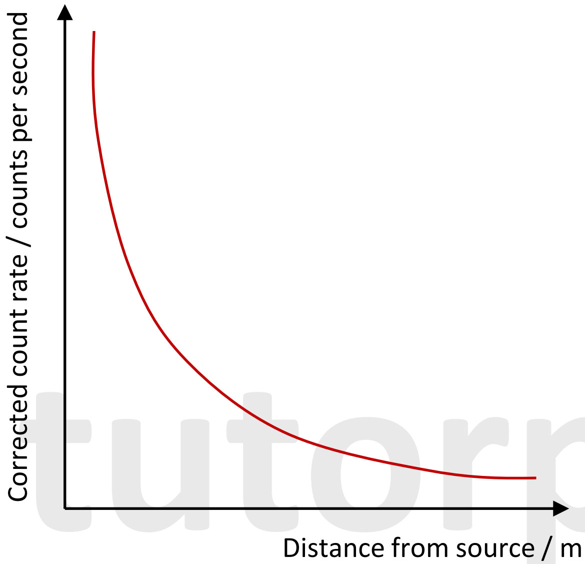
Experimental verification of Inverse-Square Law for Gamma Radiation (AQA Only)

Conclusion:



The graph should show that as the distance doubles, the corrected count rate should drop to a quarter of its original value, proving the inverse square law.

Experimental verification of Inverse-Square Law for Gamma Radiation (AQA Only)

Safety:

Gamma radiation sources should always be stored in a lead box (because the box will absorb the radiation). Do not take out the source from the box until you need to use it, and put them away as soon as you're done. Ensure that the radioactive source is out of its box for the shortest time possible.

Using a radioactive source gets substantially more harmful as you move closer to the source (as the intensity of the radiation increases), according to the inverse square law. Therefore, when moving a source through the lab, you should always keep it away from your body. To reduce the amount of radiation received by the body, always use long handling tongs.

The Nature of Radioactive Decay

Listening to the clicks from a Geiger counter placed near a weak radioactive source reveals that the counter's clicks are completely random, and it's impossible to predict when the next click will be heard. This demonstrates:

Radioactive decay is a random process.

In a stable nuclei, the attractive strong nuclear forces between all nucleons and the repulsive electrostatic forces between protons are balanced.

Radioactive materials have atoms of unstable nuclei in which the repulsive forces are larger than the attractive forces, and these nuclei emit radiation $(\alpha, \beta\ or\ \gamma)$ in order to become more stable.

Radioactive Decay is Spontaneous

When we refer to radioactive decay as "spontaneous," we mean that it occurs on its own (i.e. there is nothing that can be done to the nucleus to cause or prevent it from decaying).

We cannot predict when a nucleus will decay because there's no change in the nucleus that would signal it's about to decay.

Temperature, pressure, humidity, chemical combinations, and other external influences have no effect on radioactive decay.

Also, since nearby nuclei do not interact with one another, each nucleus in a sample of radioactive material decays independently of its neighbours. This is due to the fact that the strong force that would cause them to interact has a very short-range force.

It is hard to predict when a nucleus will decay because it is a spontaneous and random process. However, because a sample of radioactive material always contains a large number of nuclei (for example, $1\ mole\ =\ 238g$ of uranium – 238 will contain an incredible 6.02×10^{23} nuclei), statistical methods can be used to determine what fraction of a substance will have decayed on average over a given time interval.

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Activity (A) and decay constant (λ)

The rate at which the nuclei of a radioactive sample will decay is measured by its activity (A).

Activity is measured in decays per second (or hour or day).

$$A = -\frac{\Delta N}{\Delta t} \ldots\ldots\ldots (1)$$

Where:

N = number of unstable nuclei in a sample.

The activity of a sample is measured in Becquerels (Bq) where 1 Bequerel is equal to 1 decay/second $(1\ s^{-1})$.

The minus sign in this equation is because ΔN is always a decrease.

Therefore activity (A) of a radioactive sample is directly proportional to the number of unstable nuclei in the sample, N, at any given time. For example, a sample twice as large would result in twice as many decays per second for a given isotope.

Thus, the activity (A) of a sample with N undecayed nuclei can also be determined by the formula below:

$$A = \lambda N \ldots\ldots\ldots (2)$$

Where:

A = activity in Bq

λ = decay constant in s^{-1}

N = number of unstable nuclei in sample

The decay constant, λ, is the constant of proportionality. It is a measure of how quickly an isotope will decay, and is the probability of a certain nucleus decaying per unit time – the larger the value of λ, the faster the rate of decay.

To define it mathematically:

The decay constant (λ) is defined as the fraction of the total number of nuclei present in a sample of radioactive material that decays per second.

$$\boldsymbol{\lambda = \frac{A}{N}}$$

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Activity (A) and decay constant (λ)

Consider the following example to better understand what decay constant (λ) means:

The initial activity of a radioactive sample containing 3.0×10^8 undecayed nuclei is $6.0 \times 10^4 Bq$.

This means that every second 6.0×10^4 nuclei will decay.

As a result, the fraction of total nuclei present that decays each second is:

$$\frac{6.0 \times 10^4\ Bq}{3.0 \times 10^8} = 2.0 \times 10^{-4} s^{-1}$$

Thus $2.0 \times 10^{-4} s^{-1}$ is the decay constant λ.

Activity (A) and decay constant (λ)

Combining equations (1) and (2) from the previous page gives you the rate of change of the number of unstable nuclei:

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

Where:

ΔN = change in the number of unstable nuclei

Δt = change in time

$\frac{\Delta N}{\Delta t}$ = rate of change of number of unstable nuclei, s^{-1}

λ = decay constant, s^{-1}

N = number of unstable nuclei in a sample

Worked example:

The decay constant of a radioactive isotope is $1.25 \times 10^{-4} s^{-1}$. What is the rate of change of N for a sample containing 8.5×10^{20} nuclei?

$$\frac{\Delta N}{\Delta t} = -\lambda N = -(1.25 \times 10^{-4})(8.5 \times 10^{20}) = -1.06 \times 10^{17} s^{-1}$$

Activity (A) and decay constant (λ)

Note:

- If in a problem, the mass (m) of the radioactive sample is given instead of the number of nuclei present (N), N can be calculated using:

$$N = \frac{mN_A}{M_A}$$

Where:

- N_A = Avogadro constant (=$6.02 \times 10^{23}\ mol^{-1}$)
- M_A = relative atomic mass

You might also be asked to use a molar mass to calculate the number of atoms (or nuclei) in a sample. A material's molar mass is the mass of 1 mole of the substance (typically in grams per mole, $g\ mol^{-1}$), and is equal to its relative atomic mass or relative molecular mass.

The number of moles in a sample can be calculated by dividing the total mass of the substance by the substance's molar mass. The number of atoms can then be calculated by multiplying the number of moles, n, by the Avogadro constant, N_A.

$$N = nN_A$$

Where:

N = number of atoms in a sample

n = the number of moles in a sample, mol

- Activity cannot be measured directly. This is due to the fact that we are unable to detect all of the radiation emitted by a sample (some of the radiation gets past the detector while some is absorbed by the sample).
- As a result, measurements give a count rate (R) that is much lower than the activity (A).

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Activity (A) and decay constant (λ)

Worked example

12g of the radioactive isotope ^{234}Pa is present in a sample. Calculate the activity and the number of atoms of ^{234}Pa that are present.

The decay constant for this isotope is $2.87 \times 10^{-5} s^{-1}$ and its molar mass is $234.0\ g\ mol^{-1}$*.

Step 1: Calculate the number of moles in the sample

$$moles = 12\ g \div 234.0\ g\ mol^{-1} = 0.0512 mol$$

Step 2: Calculate the number of ^{234}Pa atoms, N, in the sample:

$\therefore N = nN_A = 0.0512\ mol \times 6.02 \times 10^{23} = 3.087 \times 10^{22}$ atoms

Step 3: Now you have everything to calculate the activity:

$$A = \lambda N = 2.87 \times 10^{-5} \times 3.087 \times 10^{22} = 8.86 \times 10^{17}\ Bq$$

**The fact that ^{234}Pa has a molar mass of $234.0\ g\ mol^{-1}$ is no accident - keep in mind, that a sample's molar mass is equal to its mass number if there are no additional atoms present.*

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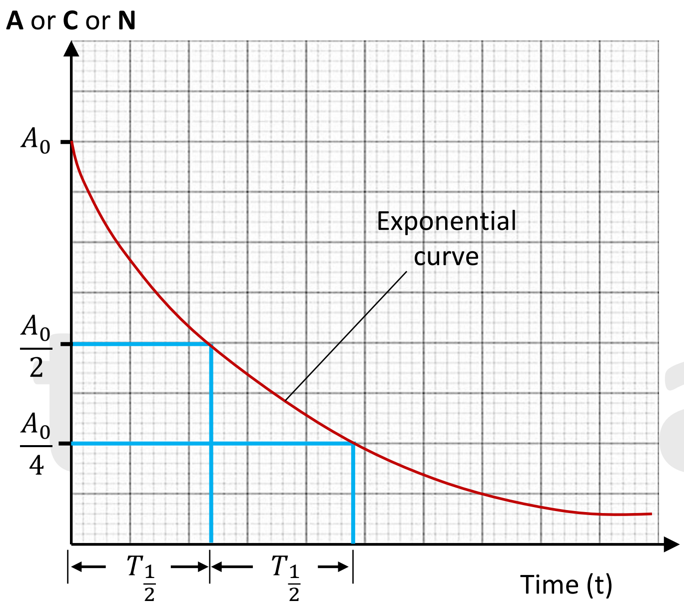
Radioactive Decay Equations and Graphs

When the activity (A), corrected count rate (C), or number of unstable nuclei remaining (N) for a particular sample of a radioactive material are plotted against time (t), an exponential decay curve is obtained as shown below:



The graph shows how a radioactive sample's activity (A) or number of remaining unstable nuclei (N) decreases exponentially with time (t).

Radioactive Decay Equations and Graphs

The decay graph is represented by a mathematical equation of the following form:

$$x = x_0 e^{-\lambda t}$$

In terms of activity (A), undecayed nuclei (N) or corrected count rate (C), the equation can be written as:

$$A = A_0 e^{-\lambda t}$$
$$N = N_0 e^{-\lambda t}$$
$$C = C_0 e^{-\lambda t}$$

Where:

- A = the activity in Bq
- A_0 = the activity at $t = 0$
- N = the number of unstable nuclei remaining
- N_0 = the original number of unstable nuclei
- N = the corrected count rate at time t
- C_0 = the original corrected count rate at $t = 0$
- λ = the decay constant in s^{-1}
- t = time in s

Remember:

- When using the equation the unit of (λ) and (t) must be the compatible.
  - For example, if λ is in s^{-1}, then t must be in s.
  - If λ is in $hours^{-1}$, the t must be in hours, etc…
- 'e' is the exponential function and can be found on a scientific calculator.

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Half-Life

The HALF-LIFE $\left(T_{\frac{1}{2}}\right)$ of a radioactive sample is defined as:

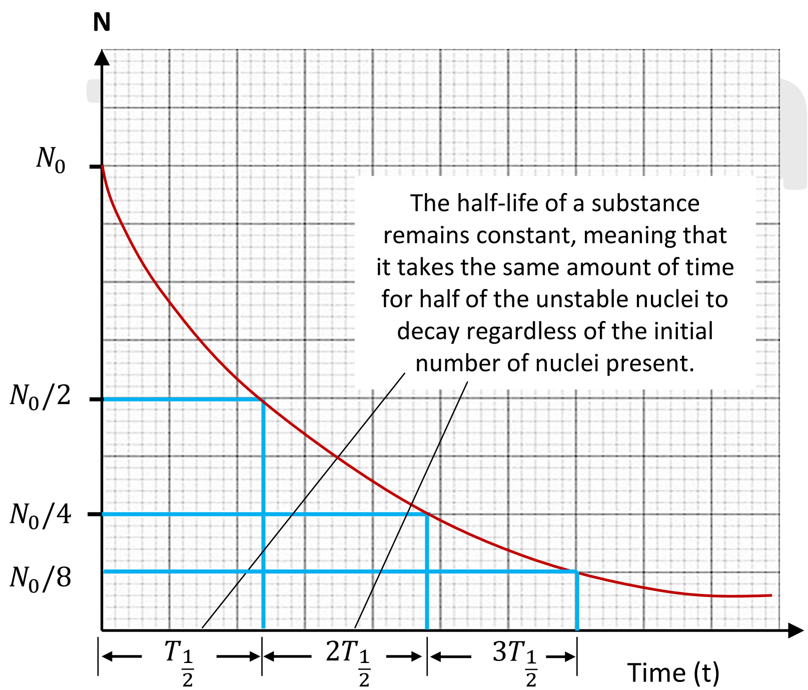
- The average amount of time it takes for half of the nuclei originally present to decay.

Or

- The mean time taken for the activity of the sample to decrease to half its initial value.

Calculating half-life from decay curves

A decay curve can be used to calculate an isotope's half-life, for example:



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Half-Life

- When $t = 0$, read off the value of the unstable nuclei. This is the nuclei originally present before decaying.
- Then, on the y-axis, go to half the original number of unstable nuclei.
- From this point draw a horizontal line to the curve, then a vertical line down to the x-axis. When the line crosses the x-axis, read off the half-life value.
- Check your answer by repeating the steps for a quarter of the nuclei originally present. By doing this you will obtain the half-life. Check to see that the half-life is the same for the half and the quarter of the original nuclei present.

Following the steps above, a half-life can be calculated from an activity-time or count rate-time graph.

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Half-Life Equation

You can derive an equation for half-life from the equation: $A = A_0 e^{-\lambda t}$

When 1 half-life has passed $\left(i.e. when\ t = T_{\frac{1}{2}}\right)$, the initial activity, A_0 will have reduced to $A_0/2$.

Therefore:

$$\frac{A_0}{2} = A_0 e^{-\lambda T_{\frac{1}{2}}}$$

Dividing both sides by A_0 gives:

$$\frac{1}{2} = e^{-\lambda T_{\frac{1}{2}}}$$

Taking natural logs of both sides gives:

$$\text{In}\left(\frac{1}{2}\right) = -\lambda T_{\frac{1}{2}}$$

This is because $\frac{1}{2} = 2^{-1}$

Now following the laws of logarithms: $In\left(\frac{1}{2}\right) = In(2^{-}) = -In(2)$

So:

$$-\text{In}(2) = -\lambda T_{\frac{1}{2}}$$

From which we get:

$$\text{In}(2) = \lambda T_{\frac{1}{2}}$$

Therefore half-life is:

$$T_{\frac{1}{2}} = \frac{In(2)}{\lambda}$$

Note: when using this equation, the unit of λ and $T_{\frac{1}{2}}$ must be compatible.

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Radioactive decay curve represented as a straight line

The natural logarithm function, $In\ x$, is the inverse exponential function (i.e. if $y = e^x$, then $In\ y = x$).

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

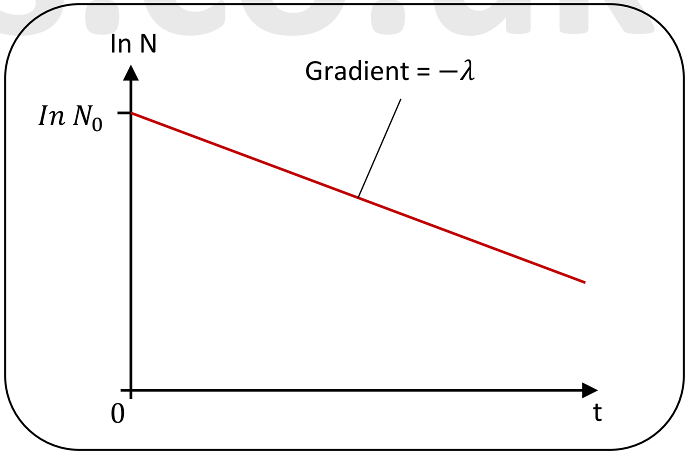
Can be expressed as: $\text{In}\ N = In\ N_0 - \lambda t$

Re-arranging gives: $\text{In}\ N = -\lambda t + In\ N_0$

When compared to the equation for a straight line: $y = mx + c$

So the graph of $In\ N$ against t yields a straight line with:

- Gradient = $-\lambda$
- y-intercept = $In\ N_0$



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Half-Life Experiment

The half-life of a radioactive isotope like protactinium can be determined experimentally.

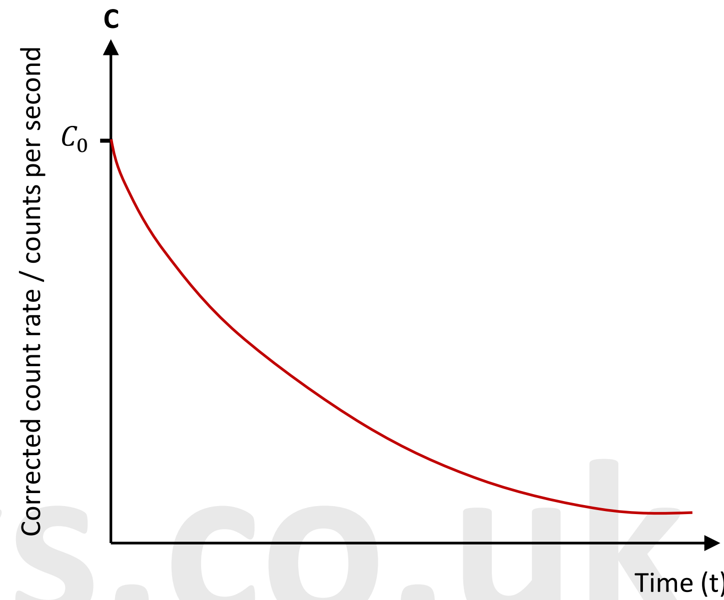
Apparatus:

- Radioactive source (protactinium bottle)
- Geiger-Muller tube
- Counter
- Stopwatch

Method:

1. Before the source is used measure the background radiation with the G-M tube.
2. Shake the bottle containing uranium salt solution and protactinium in an immiscible layer of solvent. This will allow the for the layers to be mixed.
3. As soon as the two layers have separated, start the counter and the stop watch. You will be measuring the protactinium's beta decay. The uranium sample decays as well, but it emits alpha radiation, which the bottle absorbs.
4. Record the count every 10 seconds. Do this for about 5 minutes.
5. Subtract the background count rate from each count rate measurement, and you'll get the actual count rate from the source.
6. Now plot the actual count rate of the source against the time allowing the half life to be determined.

Half-Life Experiment



Modelling Decay

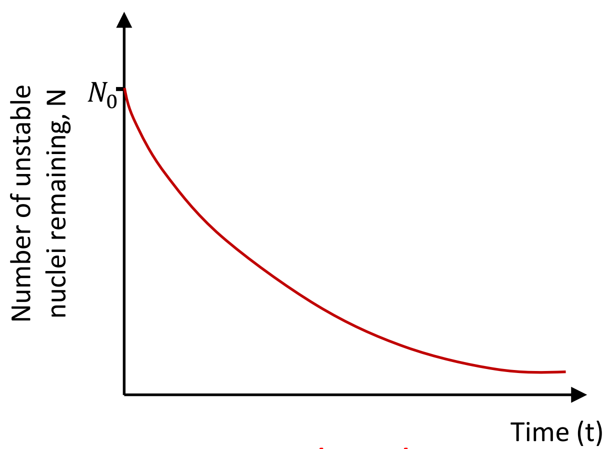
Dice

Radioactive decay is a random process in which an unstable nucleus decays with a constant probability. This probability is given by the decay constant.

The result of rolling a fair 6-sided dice is also random with a constant probability – the chance of rolling any one number is 1/6. With these similarities, you can use dice to simulate radioactive decay, with each dice representing an unstable nucleus.

For a good simulation you need at least 100 dice to represent unstable nuclei. Roll all the dice at once and count how many of them landed on a 6 – these dice represent the nuclei that have decayed. In a table, record the total number of dice rolled as well as the number of dice that have 'decayed.' Remove the 'decayed dice,' then reroll the remaining dice.

Continue until all of the dice have 'decayed'. Each roll represents one unit of time in the radioactive sample's lifespan. When you plot the number of dice thrown each time (i.e. the number of unstable nuclei left in the sample, N) against time, you'll see the same exponential relationship for radioactive decay, as shown below.



Modelling Decay

Spreadsheet modelling

A spreadsheet can be used to model radioactive decay. You'll need to apply the following equation to predict the decay:

$$\frac{\Delta N}{\Delta t} = -\lambda N \ldots\ldots\ldots (1)$$

Where:

ΔN = change in the number of unstable nuclei

Δt = change in time

$\frac{\Delta N}{\Delta t}$ = rate of change of number of unstable nuclei, s^{-1}

λ = decay constant, s^{-1}

N = number of unstable nuclei in sample

The process of radioactive decay is an iterative one (i.e. when the same procedure is repeated multiple times).

So, if you know the decay constant, λ, and the number of undecayed nuclei in the original sample, N_0, you can use a spreadsheet to complete several iterations and model the decrease in the number of unstable nuclei in a sample of an isotope.

Modelling Decay

Spreadsheet modelling

To create the spreadsheet, follow the steps below:

1) Create a spreadsheet with column titles for time (t), ΔN and N (number of radioactive nuclei left in the sample) as well as a single data input cell for each of Δt and λ.

By rearranging equation (1) from the previous page, you can get ΔN:

$$\Delta N = -\lambda N \times \Delta t$$

2) Choose a Δt, such as $1\ s$ - this represents the time interval between the values of N that the spreadsheet will calculate.

3) Then the amount of undecayed nuclei remaining after each time interval can be calculated by inputting formulas in the cells of the spreadsheet.

Data input cells	**Δt in seconds (s)**	**1**
	λ in s^{-1}	0.1

t* in *s	**ΔN (from equation)**	***N***
$t_0 = 0$		N_0 = initial number of undecayed nuclei in sample
$t_1 = t_0 + \Delta t$	$(\Delta N)_1 = -\lambda \times N_0 \times \Delta t$	$N_1 = N_0 + (\Delta N)_1$
$t_2 = t_1 + \Delta t$	$(\Delta N)_2 = -\lambda \times N_1 \times \Delta t$	$N_2 = N_1 + (\Delta N)_2$

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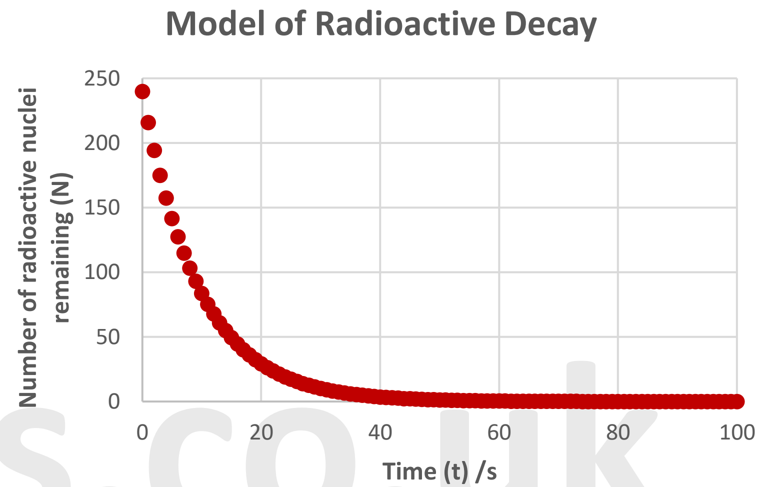
Modelling Decay

Spreadsheet modelling

After that, you can plot a graph of N against t, which should look like this:



To get a nice shape, run a 100 iterations (i.e. 100 units of time) with a time interval (Δt) of 1 and a decay constant (λ) of 0.1. However, you can play around with the numbers to create a nice curve.

See how I used the formulas to model radioactive decay in Excel on the next page.

Before you try to model anything, make sure you're comfortable with your spreadsheet tool (such as Microsoft Excel). You'll need to know how to reference and do simple cell calculations. If you don't, go to tutorpacks.co.uk to see how I used Excel to model radioactive decay.

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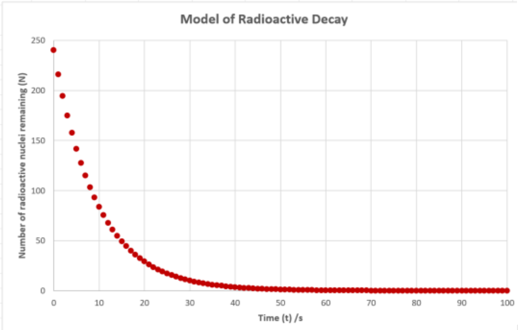
Modelling Decay

Spreadsheet modelling

Modelling Radioactive Decay Using Excel

Δt in seconds	1
Decay constant (λ) in per second	0.1

Time, t in seconds (s)	ΔN (from equation)	Number of radioactive nuclei remaining, N
0		240
1	-24	216
2	-21.6	194.4
3	-19.44	174.96
4	-17.496	157.464
5	-15.7464	141.718
6	-14.17176	127.546
7	-12.754584	114.791
8	-11.4791256	103.312
9	-10.33121304	92.981
10	-9.298091736	83.683
11	-8.368282562	75.315
12	-7.531454306	67.783
13	-6.778308876	61.005
14	-6.100477988	54.904
15	-5.490430189	49.414
16	-4.94138717	44.472
17	-4.447248453	40.025
18	-4.002523608	36.023
19	-3.602271247	32.420
20	-3.242044122	29.178
21	-2.91783971	26.261
22	-2.626055739	23.635
23	-2.363450165	21.271
24	-2.127105149	19.144
25	-1.914394634	17.230
26	-1.72295517	15.507
27	-1.550659653	13.956



Remember the time column starts at 0 and goes up to 100**.**

Modelling Decay

Spreadsheet modelling

To create the radioactive model, I entered the following formulas into the cells:

Modelling Radioactive Decay Using Excel

Δt in seconds	1
Decay constant (λ) in per second	=0.1

Time, t in seconds (s)	ΔN (from equation)	Number of radioactive nuclei remaining, N
=0		240
=B9+$C$4	=-$C$5*D9*$C$4	=D9+C10
=B10+$C$4	=-$C$5*D10*$C$4	=D10+C11
=B11+$C$4	=-$C$5*D11*$C$4	=D11+C12
=B12+$C$4	=-$C$5*D12*$C$4	=D12+C13
=B13+$C$4	=-$C$5*D13*$C$4	=D13+C14
=B14+$C$4	=-$C$5*D14*$C$4	=D14+C15
=B15+$C$4	=-$C$5*D15*$C$4	=D15+C16
=B16+$C$4	=-$C$5*D16*$C$4	=D16+C17
=B17+$C$4	=-$C$5*D17*$C$4	=D17+C18
=B18+$C$4	=-$C$5*D18*$C$4	=D18+C19
=B19+$C$4	=-$C$5*D19*$C$4	=D19+C20
=B20+$C$4	=-$C$5*D20*$C$4	=D20+C21
=B21+$C$4	=-$C$5*D21*$C$4	=D21+C22
=B22+$C$4	=-$C$5*D22*$C$4	=D22+C23
=B23+$C$4	=-$C$5*D23*$C$4	=D23+C24
=B24+$C$4	=-$C$5*D24*$C$4	=D24+C25
=B25+$C$4	=-$C$5*D25*$C$4	=D25+C26
=B26+$C$4	=-$C$5*D26*$C$4	=D26+C27
=B27+$C$4	=-$C$5*D27*$C$4	=D27+C28
=B28+$C$4	=-$C$5*D28*$C$4	=D28+C29
=B29+$C$4	=-$C$5*D29*$C$4	=D29+C30
=B30+$C$4	=-$C$5*D30*$C$4	=D30+C31
=B31+$C$4	=-$C$5*D31*$C$4	=D31+C32
=B32+$C$4	=-$C$5*D32*$C$4	=D32+C33
=B33+$C$4	=-$C$5*D33*$C$4	=D33+C34
=B34+$C$4	=-$C$5*D34*$C$4	=D34+C35
=B35+$C$4	=-$C$5*D35*$C$4	=D35+C36

On tutorpacks.co.uk, I have attached the excel file so you can play around with the model by changing the values.

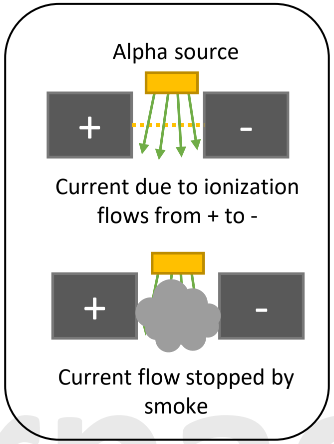
Applications of Nuclear Radiation

What a radioactive source can be used for often depends on its ionising properties.

Alpha Radiation

As we already know, radiation ionises the air it passes through, with a-particles being the most ionising. This process is well-used by smoke detectors.

In the diagram, a-particles from a weak, americium-241 source pass through an ionisation chamber. The alpha particles cause ionisation of the air molecules, resulting in a small, constant current that is detected by the current detector in this air-filled region between two electrodes.



Smoke entering the chamber absorbs a-particles, reducing ionisation and thus the detected current. The electronic circuit detects the decrease in current and sounds the alarm.

Note:

An alpha-particle source is used since alphas will cause enough ionisation to provide a detectable current.

Since Americium-241 has a half-life of 432 years, it easily outlasts the smoke detector's lifetime.

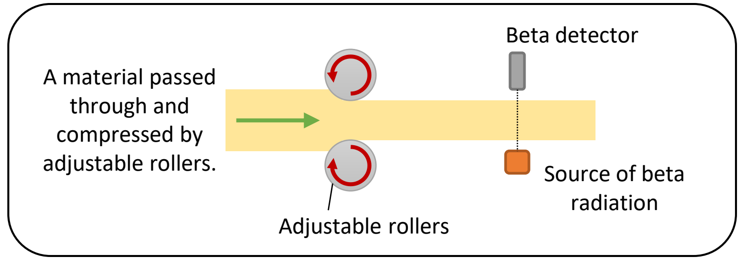
The smoke detector is safe because the source is only weakly radioactive, and the alpha particles are stopped by the plastic outer covering and have a range of only 5-10cm in air.

Although alpha particles can not penetrate the skin, they can be harmful if consumed. They ionise bodily tissue in a small area quickly, producing significant harm.

Applications of Nuclear Radiation

Beta-Minus Radiation

Beta radiation can be used to adjust the thickness of sheets of material like paper, aluminium foil, or steel.



As the material passes through the rollers, it flattens out. On one side of the material, a radioactive source is installed, and on the other, a radioactive detector. The more radiation the material absorbs and stops from reaching the detector, the thicker it is. The rollers move closer together to make the material thinner if too much radiation is absorbed. They move further apart if not enough radiation is absorbed.

Note:

This process cannot use alpha radiation because it would not penetrate the material, and gamma radiation cannot be used because the thicknesses used are too thin to stop gamma radiation from passing through the sheet of material.

Beta-minus particles have a lower ionising potential than alpha radiation. This is due to its smaller mass and charge and because it has a lower interaction with atoms before losing energy. This lower number of interactions means that beta radiation causes much less damage to body tissue.

Applications of Nuclear Radiation

Gamma radiation

Since gamma radiation is much weaker than beta radiation in terms of ionisation, it will do even less harm to body tissue. It can therefore be utilised in medicine.

Radioactive tracers are used to aid in the diagnosis of individuals who do not require surgery. To avoid extended radiation exposure, a radioactive source with a short half-life is swallowed or injected into the patient. The released gamma rays are then detected using a detector, such as a PET scanner.

Gamma rays can be used to cure cancerous tumours by destroying the cells and, in some cases, curing cancer patients. Radiation affects all cells, cancerous or not, hence a rotating beam of gamma rays is used. This minimises harm to surrounding tissue while providing a high dose of radiation to the tumour at the rotation's centre.

However, damage to other, healthy cells cannot be totally avoided, and patients may have side effects such as weariness, reddening, or discomfort of the skin as a result of treatment. Some gamma ray therapies can have long-term consequences, such as infertility.

There are advantages and disadvantages to using radiation in medicine. The goal is to try to adopt methods that reduce risk (e.g., using staff shielding when doing those procedures, rotating the beam, etc.) while still giving you the outcomes you desire

Applications of Radioactive Substances

Radioactive dating (e.g. carbon-dating)

Carbon-14, a radioactive isotope*, is used in radioactive dating (e.g. carbon dating). As part of photosynthesis, living plants absorb carbon dioxide from the atmosphere, including the radioactive isotope carbon-14. Carbon-14 activity in the plant begins to decline as they die, with a half-life of roughly 5730 years.

Archaeological findings made from dead plants (e.g., wooden structures) or even dead organisms can be examined to determine the current amount of carbon-14 in them and date them.

However, radioactive dating can be difficult to use to determine a reliable age because:

- There may be uncertainty in the amount of carbon-14 that existed thousands of years ago.
- For man-made objects crafted from natural materials like wood, you only find the age of the material used – not the object itself.
- Other radioactive sources could have contaminated the object.

*Radioactive isotopes contain an unstable atomic nucleus (because of the balance between the neutrons and protons) and emits energy and particles (alpha, beta, and gamma) as it changes to a more stable form.

Applications of Radioactive Substances

Medical Diagnosis

Medical tracers, which are radioactive chemicals used to show tissue or organ function, commonly use technetium-99m. The tracer is injected or swallowed by the patient, and it travels through the body to the target position. The emitted radiation is recorded, and an image of the inside of the patient is created.

Technetium-99m is suited for this application because it emits γ-radiation, has a half-life of 6 hours (long enough for data to be recorded, but short enough to keep the radiation to a manageable level), and decays to a much more stable isotope.

Continue to the next page

Please see '10.1.2 Radioactivity worked examples' pack for exam style questions.

For more revision notes, tutorials and worked examples please visit www.tutorpacks.co.uk.