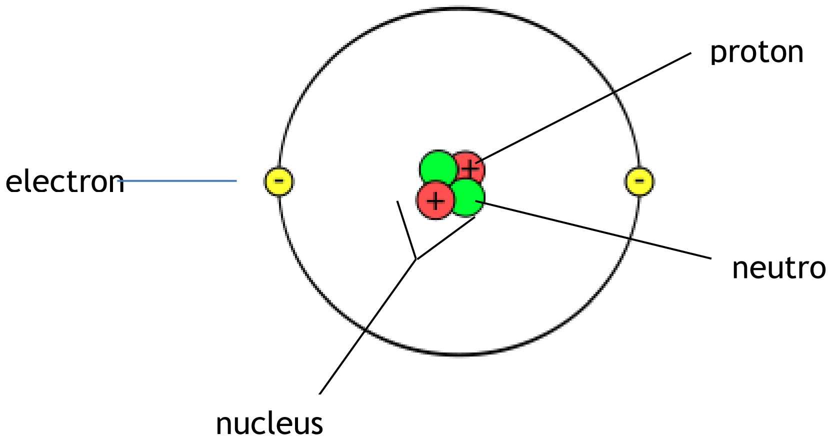
N5: RADIATION NOTES

STRUCTURE OF THE ATOM AND IONISING RADIATION

THE ATOM

Before we can understand ionising radiation, which originates from the nucleus of atoms we must have an idea of the structure of the atom.



- The neutrons and the protons are in the centre or nucleus of the atom.
- The electrons are moving around the nucleus.
- *A proton has a positive charge. (p)*
- *An electron has a negative charge.(e)*
- *A neutron is uncharged.(n)*

Normally the atom has no overall charge. It is said to be *neutral* because the number of protons in the nucleus is equal to the number of electrons in the orbits.

NUCLEAR RADIATION

Everything in nature prefers to be in a stable state of minimum energy. The unstable nuclei are unstable because they have too much energy. They get rid of this energy by emitting some form of radiation (either particles or electromagnetic waves). This radiation is nuclear radiation because it comes from the nucleus of an atom. These atoms are said to be radioactive

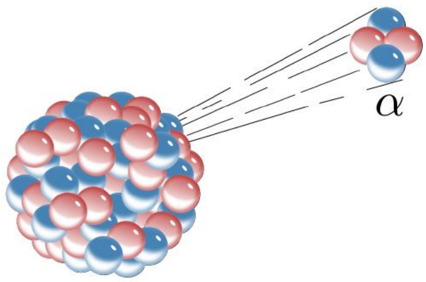
Nuclear radiation can come from natural sources such as cosmic rays and naturally occurring radioactive materials such as uranium. It can also come from artificial sources such as man-made radioisotopes such as plutonium.

Nuclear radiation can be used in medicine to sterilise instruments by killing germs and bacteria. It can also be used to kill the cells which make up a cancerous tumour.

There are some atoms which have unstable nuclei. (Nuclei is the plural of nucleus)

Types of Radiation

Alpha Particles



An alpha particle consists of two protons and two neutrons. They have the same structure as a helium nucleus, so we can write it down as $^{4}_{2}He$

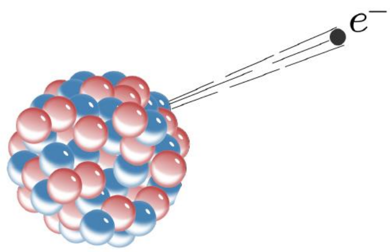
The top number 4 is the total number of protons and neutrons (or nucleons- things in the nucleus) and the bottom number is the number of protons. If we take the bottom number from the top number it will give us the number of neutrons.

Beta Particles

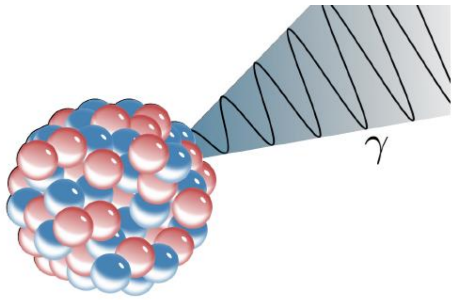
A beta particle is an electron which comes from the nucleus. But there aren't any electrons in the nucleus so where do these come from? A neutron changes into a proton and an electron

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

Neutron → proton + electron



Gamma Radiation



Gamma rays are not particles but high energy electromagnetic radiation. Gamma rays carry excess energy from the nucleus. There is no change in the atomic structure before and after the emission of gamma rays unlike the other two particles where new atoms are formed.

Ionisation

There are some atoms which have unstable nuclei which throw out particles to make the nucleus more stable in the materials through which they pass. These atoms are called radioactive. The particles thrown out cause ionisation and are called ionising radiations.

There are three types of ionising radiation: Alpha beta and gamma. Energy may be absorbed from alpha, beta or gamma by the material. When an alpha particle collides with an atom an electron can be “knocked off”. The alpha particle transfers energy to the electron and the alpha particle slows down.

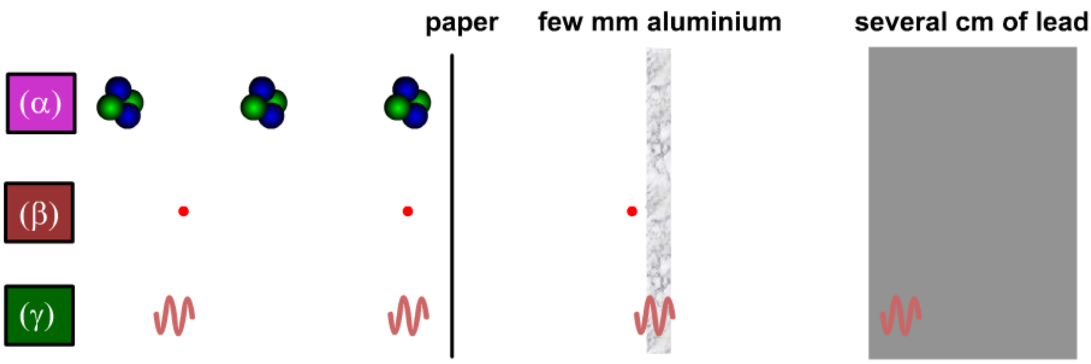
The process by which nuclear radiation damages cells is known as **ionization**. This is where electrons are stripped from their atoms. Alpha radiation is far more ionising than beta or gamma radiation, we say alpha particles produce greater ionisation density than beta particles or gamma radiation.

Ionisation is the gaining or losing of electrons from atoms.

Alpha, beta and gamma require different materials to absorb them.

Alpha particles are absorbed by a thin sheet of paper. Beta particles are absorbed by a few mm of aluminium and gamma rays required several cm of lead or several metres of concrete to absorb most of them.

Alpha particles transfer energy to the air by causing ionisation during collisions. The range of alpha particles in air is a few cm. The range of beta particles in air is a few metres. Gamma rays are only very slightly absorbed by air.



Summary

type of radiation	symbols		nature	absorbed by
alpha	α	^4_2He	two protons and two neutrons (helium nucleus)	sheet of paper, few cm of air
beta	β	$^{0}_{-1}e$	fast-moving electron	few cm of aluminium
gamma	γ		electromagnetic wave	most few m of lead

*The **activity** or a radioactive source is the number of nuclei decays every second.*

It is calculated by $A = \frac{N}{t}$

where

A is the activity in becquerels (Bq) Or counts per min/ counts per sec/ decays per sec etc.

N is the number of nuclei that decay

and *t* is the time in seconds (s)

A source has an activity of 1 Bq if one of its atoms disintegrates each second

In real life, the becquerel is a very small unit. Radioactive sources in medicine have activities measured in kilobecquerels (kBq) or megabecquerels (MBq)

Background radiation

Background radiation is all around us. Some of it comes from natural sources and some comes from artificial sources. Humans have always been exposed to a continual 'background' of radiation. Background radiation can be divided into two groups, according to the source, naturally occurring radiation and artificial or manmade sources.

Natural sources

Natural sources of background radiation include:

- **Cosmic rays** - radiation that reaches the Earth from space
- **Rocks and soil** - some rocks are radioactive and give off radioactive radon gas, granite is known to be more radioactive than other rocks

Living things - plants absorb radioactive materials from the soil and these pass up the food chain.

For most people, natural sources contribute the most to their background radiation dose. Absorbed dose is measured in Sieverts and we will discuss this later.

The average annual background radiation in the UK is 2·2 mSv

Cosmic rays are high energy particles from outer space and our own sun. Primary cosmic rays (mostly protons) lose energy, by collisions in the atmosphere, and produce secondary cosmic rays, of γ-rays, electrons and neutrons that may reach the Earth's surface. Cosmic rays are more intense at high altitudes.

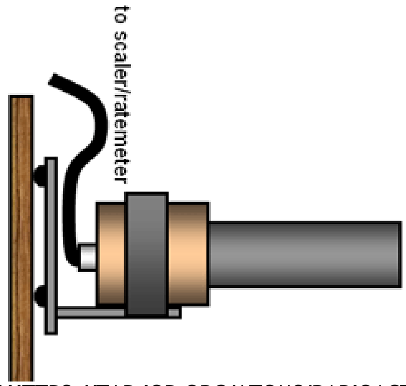
The Granite city receives about 5 times the average Equivalent dose
Rocks and soil contain traces of radioactive materials, mainly uranium-238, thorium-232 and their daughter products radium, and potassium-40. Granite is more radioactive than brick or sandstone. Areas where there are large amounts of granite have higher background rates, e.g. Aberdeen and Dartmoor.

ARTIFICIAL SOURCES

There is little we can do about natural background radiation. After all, we cannot stop eating, drinking or breathing to avoid it; but human activity has added to background radiation by creating and using artificial sources of radiation. These include radioactive waste from nuclear power stations, radioactive fallout from nuclear weapons testing and medical x-rays.

DETECTING RADIATION

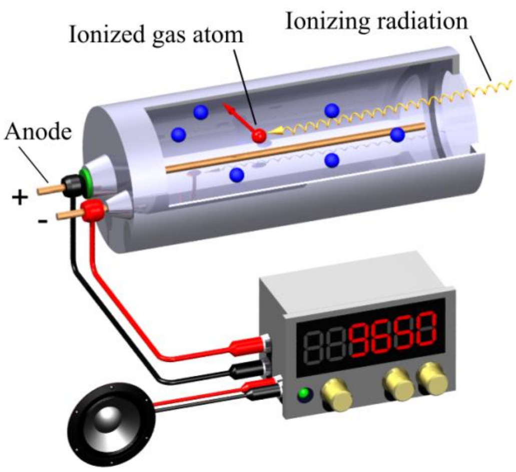
GEIGR - MULLER TUBE.



0-AHTTPS://TAP.IOP.ORG/ATOMS/RADIOACTIVITY/509/PAGE_47071.HTML

We can detect radioactivity with a Geiger - Muller tube.

Inside the tube there is a gas. When radioactivity enters the tube through a thin window, made of mica, in the front or through its walls, atoms in the gas are ionised. The electrons knocked out of the atom form an electric current- This produces a reading on a meter. This shows us that radioactivity is present. Geiger Muller tubes can detect alpha, beta and gamma radiation.

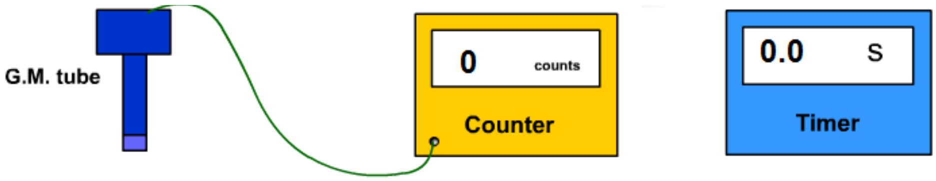


FILM BADGES

People who work with radioactivity often wear a badge containing photographic film - a film badge. When they finish work, they hand in their film badge. The photographic film inside is developed. Film badges can detect beta, gamma and X-ray radiation. We can tell how much radioactivity they have received at work by observing how fogged the film is.

A film badge can also show that radioactivity is present. When radioactivity hits photographic film, it affects the atoms on the film surface. When the film is developed, it looks foggy.

MEASURING BACKGROUND RADIATION



- Set up the apparatus as shown above.
- Connect the Geiger Müller tube to a counter or ratemeter and take a count for at least a minute.
- Record this value in your jotter.
- Repeat or complete one count for a longer period of time.
-

DOSE

ABSORBED DOSE

Ionising radiation carries energy. This energy can be absorbed by tissue and possibly cause damage to the tissue. The more energy is absorbed the more damage could occur. The amount of energy received by a substance per unit mass is known as the **absorbed dose**.

The ABSORBED DOSE, D, is the ENERGY ABSORBED PER KILOGRAM. It is measured in GRAYS, Gy.

$$D = \frac{E}{m}$$

where D is the absorbed dose in grays (Gy) 1 Gy = 1 J kg^{-1}

E is the energy in joules (J)

and m is the mass of the absorbing tissue in kilograms (kg)

EQUIVALENT DOSE

Absorbed dose does not tell the whole story of how a person would be affected by nuclear radiation. The problem with using absorbed dose is that it gives no indication of the type of radiation and the damage it causes.

So a **Radiation Weighting Factor**, w_R, is introduced to take account of the biological effect of the type of radiation. The **Radiation Weighting Factor**, w_R, is given in published tables.

This gives us a new term called **equivalent dose.** The **equivalent dose** allows us to take the type of radiation into account. It is calculated by using the equation.

equivalent dose = absorbed dose x radiation weighting factor

Equivalent dose is measured in Sieverts (Sv).

$$H = D \; x \; w_R$$

where H is the equivalent dose in sieverts (Sv)

D is the absorbed dose in grays (Gy)

and w_R is the radiation weighting factor

The equivalent dose takes account of the different susceptibilities to harm of the tissue being irradiated and is used to indicate the risk to health from ionising radiation.

The risk of biological harm from an exposure to radiation depends on:

- the absorbed dose
- the kind of radiation e.g α, β, δ
- the body organs or tissue exposed.

Equivalent dose (H) is a measure of the radiation dose to tissue where an attempt has been made to allow for the different relative biological effects of different types of ionising radiation

Here are examples of Radiation Weighting Factor for types of radiation. You are not expected to know these values but you are expected to be able to use them

Type of radiation	Radiation Weighting Factor
X-rays	1
γ rays	1
β-particles (E<30KeV)	1.7
β-particles (E>30KeV)	1
α particles	20
heavy nuclei	up to 20
protons	10
slow neutrons	2.3
fast neutrons (1Mev)	10
really fast neutrons (10Mev)	6.5

Alpha radiation has a radiation weighting factor of 20, whereas beta and gamma radiation both have a radiation weighting factor of 1.

EQUIVALENT DOSE RATE

Again, the Equivalent dose value gives no indication of the time the radiation is absorbed for. So a new quantity is produced. Equivalent dose rate is the equivalent dose absorbed in unit time and indicates the amount of radioactive dose received by a person within a certain period of time.

$$\dot{H} = \frac{H}{t}$$

($\dot{H}$ the dot indicates rate)($\dot{H}$ pronounced H-dot)

Another way of calculating the equivalent dose rate is

$$\dot{H} = \dot{D} \times w_R$$

Usual Equivalent dose rates are in mSvy^{-1} or μSvy^{-1}

The average person in the UK receives a background equivalent dose of 2·2 mSv per year.

SAFETY WITH RADIATION

There are several safety precautions that must be taken when handling radioactive substances.

- Always handle radioactive substances with forceps. Do not use bare hands.
- Wash hands thoroughly after using radioactive substances especially after using open sources or radioactive rock samples.

In addition there are several safety precautions relating to the storage and monitoring of radioactive substances.

- Always store radioactive substances in suitable lead-lined containers.
- As soon as source has been used, return it to its safe storage container,to avoid unnecessary contamination.
- Keep a record of the use of all radioactive sources.

ANNUAL EFFECTIVE DOSE EQUIVALENT LIMITS

For the public, exposure should not exceed 5 mSv in any year and should not exceed 1 mSv per year on a long term basis.

Radiation workers are permitted higher doses, because:

- they are unlikely to be either old and infirm or young and vulnerable
- they will be subject to regular medical examination
- they will have their exposure monitored.

- Average annual background radiation in UK: 2·2 mSv.
- Annual effective dose limit for member of the public: 1 mSv.
- Annual effective dose limit for radiation worker: 20 mSv.

LIMITING EXPOSURE

The 2 main precautions that you can take

1. Get as far from the source as possible (as radiation obeys the inverse square law)

2. Get a dense material between the source and the spectators.

HALF LIFE

The activity of a source decreases over time. Whilst the decay of an individual atom is completely random and unpredictable, the time taken for half the atoms in a large sample of a particular material to decay can be predicted as it will always be the same time. This is known as the **half-life**.

Half life: the time taken for half of the radioactive atoms to decay or half life is the time for the activity to decrease by half

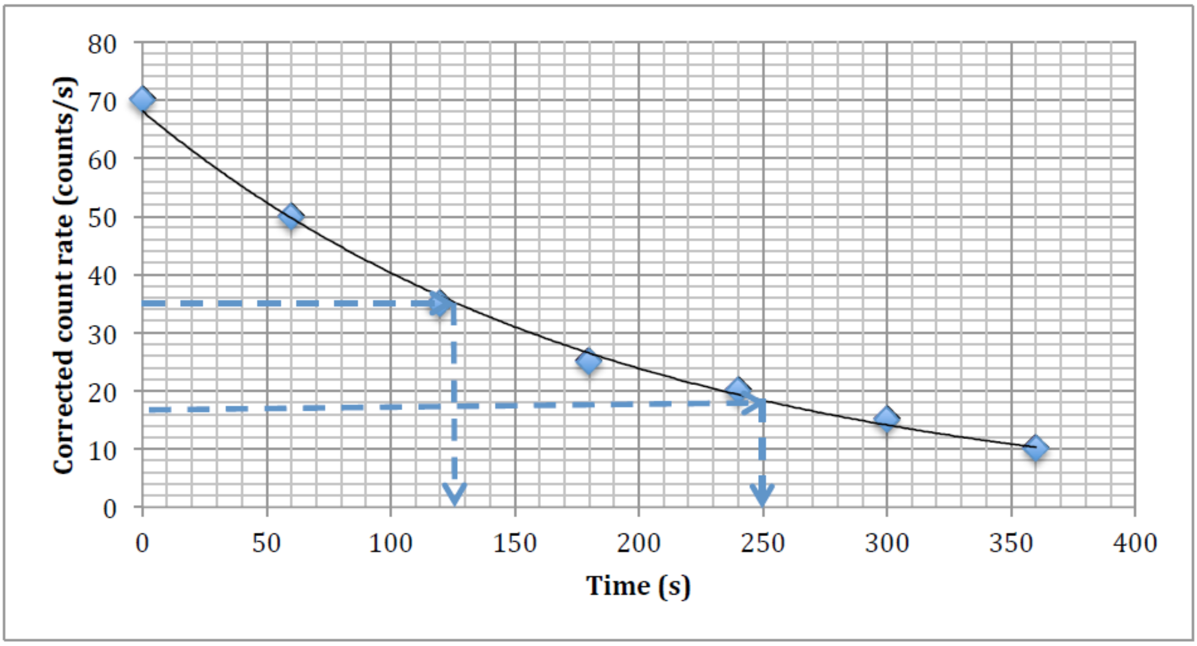
FINDING THE HALF-LIFE OF A RADIOACTIVE SOURCE

To measure the half-life of a radioactive source, the level of the background radiation is first measured. Then the count rate with the radioactive source present is measured over a suitable period of time using a suitable detector such as a Geiger-Muller tube connected to a scaler. A graph of the count rate (with the source present), corrected for background radiation, is plotted.

Different materials have different half- lives; a few are given in the table.

Atom	Half Life	Atom	Half Life
hydrogen-7	1×10^{-22} s	californium-254	60.5 days
carbon-15	2.5 s	plutonium-238	87.7 years
nobelium-259	58 minutes	uranium-238	4.5 billion years

This can be represented on a graph of activity against time as shown. The half life is the time taken for the activity of a sample to drop by half. From the graph it can be seen that the time taken to drop from 200 Bq to 100 Bq is the same amount of time taken to drop from 100 Bq to 50Bq

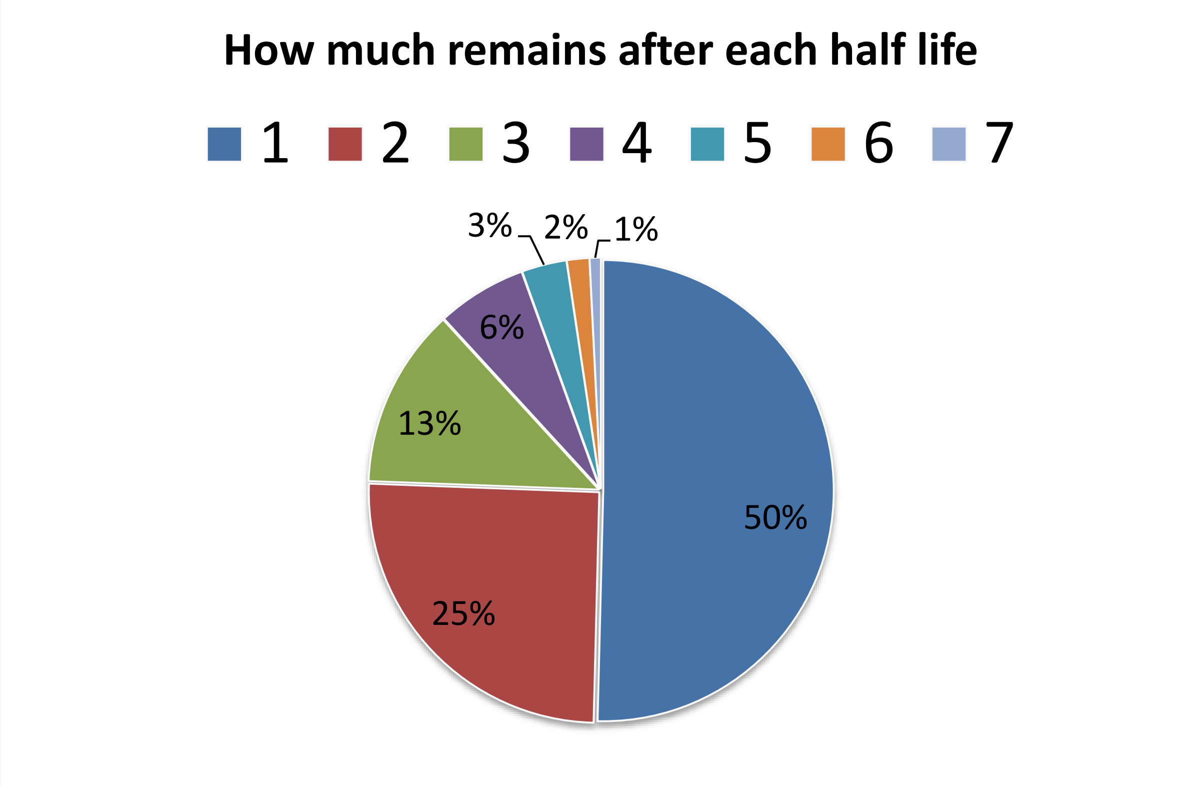


Time (s)	0	60	120	180	240	300	360
Corrected count rate (counts/s)	70	50	35	25	20	15	10

From **the best-fit line** on the graph the time taken to fall from
- 70 counts/s to 35 counts/s = 125 s
- 35 counts/s to 17.5 counts/s = 125 s

Average half-life of caesium-140 = 125 s.

Half-life can be likened to sharing a cake with friends. Your friends arrive one by one, and as each new person arrives, you offer them half the cake you have left. The first friend to arrive gets significantly more cake than the 7th friend! (as shown in the pie chart)



Half Life is the time it takes for the activity of the substance to decrease by half. (it is measured in units of time, e.g seconds, minutes, days, years, millions of years!)

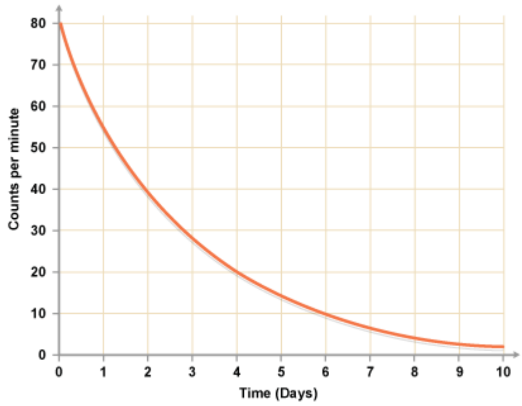
No. of half lives	fraction	Power of 2!
0	1/1	$\frac{1}{2^0}$
1	½	$\frac{1}{2^1}$
2	¼	$\frac{1}{2^2}$
3	$\frac{1}{8}$	$\frac{1}{2^3}$
4	$\frac{1}{16}$	$\frac{1}{2^4}$
5	$\frac{1}{32}$	$\frac{1}{2^5}$
6	$\frac{1}{64}$	$\frac{1}{2^6}$
n		$\frac{1}{2^n}$

After 17 half lives you would have $1/2^{17}$ of the material left

You'd have 1/131072 th of the original material left!

Radioactive decay involves a change from a high energy state to a lower energy state for the individual atoms involved. As a result of decay then there are fewer high energy, radioactive atoms. This means the overall activity will decrease over time as fewer candidate atoms are available to decay.

Radioactive decay is a random process. This means that for a radioactive source, it is not possible to predict when an atom will decay. Each atom has an equal probability to be the next atom to decay. In any radioactive source, the activity decreases with time because the number of unstable atoms gradually decreases leaving fewer atoms to decay.



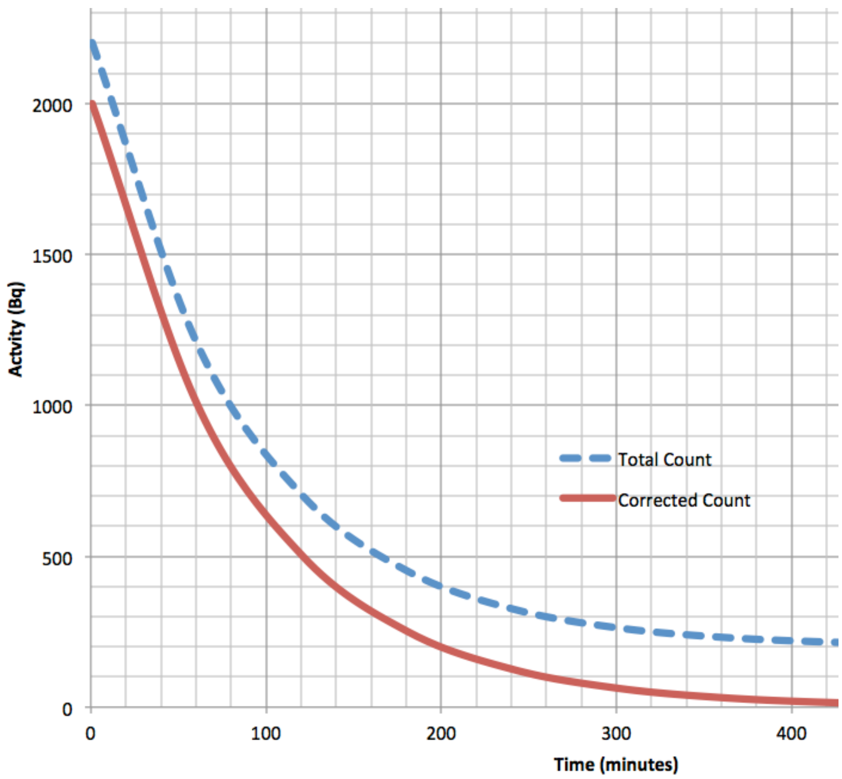
The **half-life** of a radioactive source is **the time for the activity to fall to half its original value**. Half-life is measured in units of time. This may be seconds, minutes, days or years.

Using a graph of activity versus time, it is possible to calculate the half-life of a radioactive source.

The count rate drops from 80 to 40 in two days. In the next two days, it drops from 40 to 20 - it halves. In the two days after that, it drops from 20 to 10 - it halves again - and so on. So the half life, $t_{1/2}$ = 2 days $t½$ should be the same value no matter which starting activity is selected.

CORRECTED COUNT RATE

When making accurate measurements of the decay of a radioactive source you must always use the corrected count rate. This is the count rate that is due to the source alone and not including any background radiation.
From the diagram it can be seen that incorrectly using the total count curve gives an erroneously large value for $t_{1/2}$ corrected count = total count – average background count



e.g.1 A source has an original activity of 1000 Bq. What is the half life if the activity is 15.6 Bq after one day?

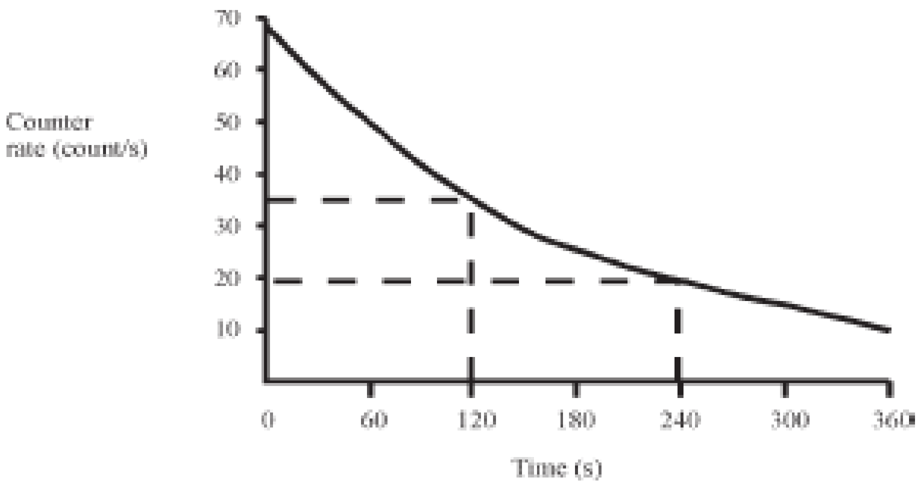
1000 $\rightarrow$ 500 $\rightarrow$ 250 $\rightarrow$ 125 $\rightarrow$ 62.5 $\rightarrow$ 31.25 $\rightarrow$ 15.6 Bq
1 2 3 4 5 6

(What to do is - Keep halving the Activity until you reach the value that you want. COUNT THE ARROWS, not the NUMBERS. The number of arrows tells you the number of half lives)

1000 ➔ 500 ➔ 250 ➔ 125 ➔ 62.5 ➔ 31.25 ➔ 15.6 Bq
➘ ➘ ➘ ➘ ➘ ➘
1 2 3 4 5 6

e.g A Geiger Muller tube and rate meter were used to measure the half-life of Caesium-140. The activity of the source was noted every 60 seconds. The results are shown in the table. By plotting a suitable graph, determine the half-life of Caesium-140.

Time (s)	*0*	*60*	*120*	*180*	*240*	*300*	*360*
Count Rate (counts/s) (corrected for background)	*70*	*50*	*35*	*25*	*20*	*15*	*10*



from the graph: time taken to fall from 70 cps to 35 c: 120s

from 35 cps to 17.5 cps: 120s

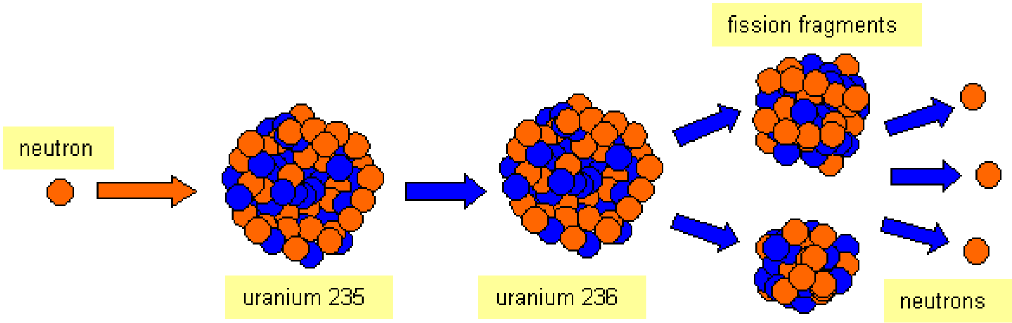
Fission and Fusion

Nuclear radiation can be used to generate energy. There are two ways in which nuclear radiation can be used to generate energy.

Nuclear fission is the process in which one nucleus splits into more than one nuclei, leading to formation of other elements and the release of energy in the process. There are two types of nuclear fission: spontaneous and stimulated fission. Some heavy nuclei are not stable so they will undergo spontaneous fission and give lighter nuclei. Sometimes fission is stimulated by collisions with other particles. For example, the fission of uranium 235 in nuclear reactors is started by the collisions with neutrons. If a neutron is fired into the nucleus of a uranium 235 atom, the atom will split into two new nuclei emitting further neutrons and releasing energy in the form of heat (i.e. the kinetic energy of the emitted nuclei).

This splitting of the atom is known as STIMULATED NUCLEAR FISSION. The new nuclei are known as fission fragments. The emitted neutrons hit other atoms causing them to split. If this process keeps going, a CHAIN REACTION results giving out huge amounts of energy in a way which is difficult to control.

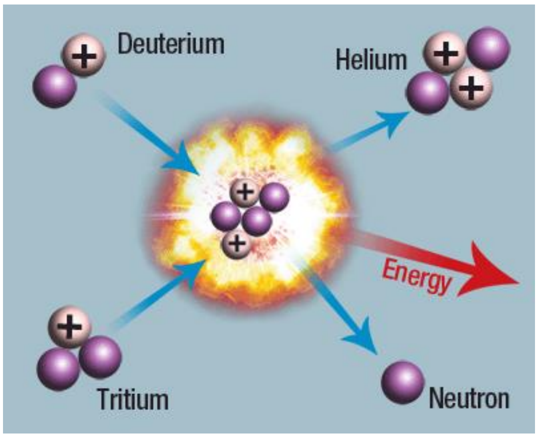
Fission



If a neutron is fired at a uranium 235 nucleus, it becomes unstable and separates into two smaller nuclei and releases some more neutrons. The mass of these nuclei and neutrons is slightly less than the mass of the original nucleus and neutron. Using the equation $E = mc^2$ we can calculate the energy released in each fission reaction. If the neutrons that are released are captured by other uranium 235 nuclei, the process can be repeated. This is known as a **chain reaction**.

In nuclear power stations, the energy released is used to heat water to produce steam to turn a turbine. This drives a generator which produces electricity.

Fusion



Fusion is a process where two smaller nuclei are combined to create a larger nucleus. Again, the total mass of the products of this reaction is less than the total mass before the reaction, allowing us to calculate the energy released by using the equation $E = mc^2$. It is thought that fusion would allow us to generate far more energy than fission at much lower risk, however we are currently unable to do this economically. Fusion is the process in which stars convert fuel to light and heat.

Note: It is important that you do not misspell fusion or fission!

Nuclear Power Stations

A nuclear power station is similar to a coal or oil fired power station, but the fuel used to produce the heat is uranium or plutonium.

The particles (or atoms) of the uranium or plutonium are spilt into smaller particles in a nuclear reactor. This is called FISSION.

When the atoms split a large amount of heat is produced, which turns water into steam. In turn the steam is used to spin a turbine, which turns a generator to produce electricity.

Using nuclear radiation to produce electricity reduces the amount of carbon dioxide released into the atmosphere. Carbon dioxide is a greenhouse gas which helps contribute to global warming. However, nuclear reactors produce radioactive waste which needs to be stored for thousands of years before it is safe.

Nuclear power stations produce radioactive waste materials, some of which have half-lives of hundreds of years. The difficulties in storing this are controversial and the decisions made will affect generations to come. Some scientists believe the containers will keep the radioactive material safe for a long time, other scientists are worried that the containers will not remain intact for such a long time.

Although nuclear power stations can produce large amounts of electricity, with no further use of fossil fuels there are other dangers involved.

Advantages of Using Nuclear Power to Produce Electricity

- Fossil fuels are running out, so nuclear power provides a convenient way of producing electricity.
- A nuclear power station needs very little fuel compared with a coal or oil-fired power station. A tonne of uranium gives as much energy as 25000 tonnes of coal.
- Unlike fossil fuels, nuclear fuel does not release large quantities of greenhouse gases or sulphur dioxide (a cause of acid rain) into the atmosphere.

- A country may not want to be reliant on imports of fossil fuels. If a country has no fossil fuels of its own it might use nuclear power for security reasons.

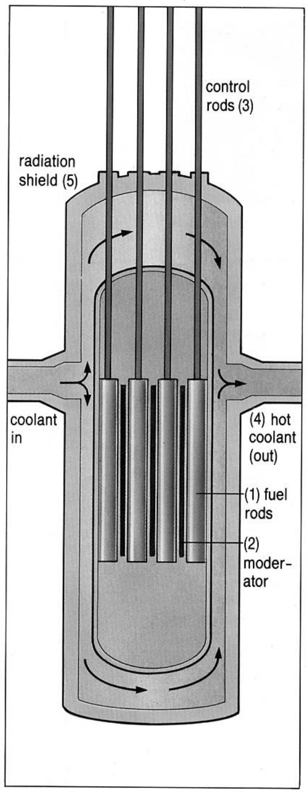
Disadvantages of Using Nuclear Power to Produce Electricity

- A serious accident in a nuclear power station is a major disaster. British nuclear reactors cannot blow up like a nuclear bomb but even a conventional explosion can possibly release tonnes of radioactive materials into the atmosphere. (The Chernobyl disaster was an example of a serious accident.)

- Nuclear power stations produce radioactive waste, some of which is very difficult to deal with. Nobody wants radioactive waste stored near them.

- After a few decades nuclear power stations themselves will have to be decommissioned.

PHYSICS THROUGH APPLICATION

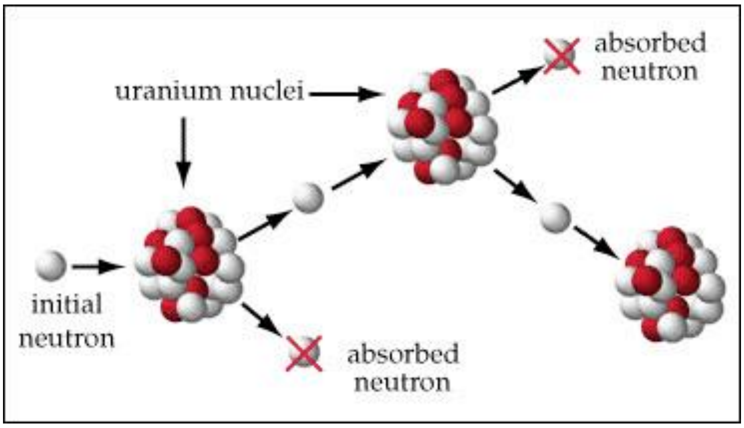


Nuclear Reactors

A nuclear reactor replaces the boiler in a fossil-fuelled power station. The five main parts of a reactor are shown here.

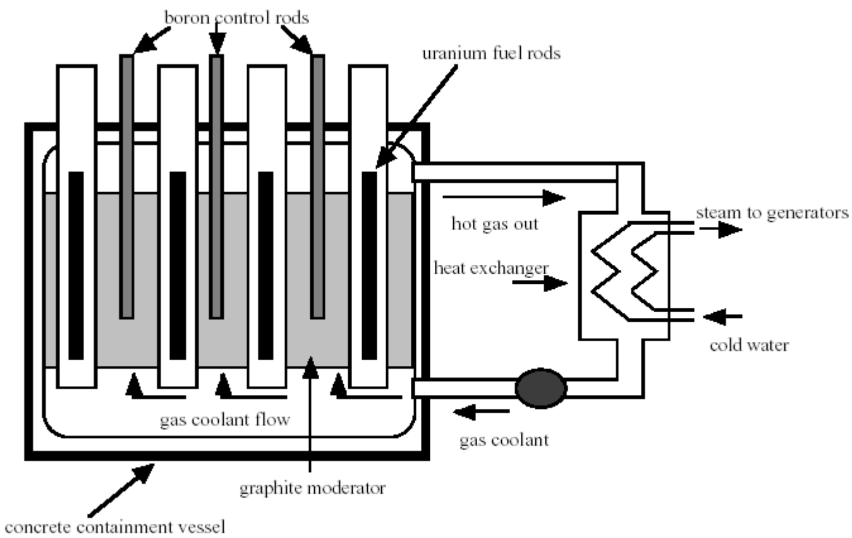
1. **Fuel:** Uranium metal was first used as fuel but today uranium dioxide is more common. The dioxide powder is compressed to form solid pellets which are loaded into narrow tubes about 3.7 m long. These are called pins and are mounted side by side into cylinders to form the fuel rods for the reactor.

2. **Control rods**: These absorb neutrons.
   To run the reactor safely we need to control the flow of neutrons. The control rods are made of a material, such as cadmium, which absorbs neutrons. By pushing the rods into the reactor neutrons are absorbed and the reaction slows down; by pulling the rods out the reaction speeds up.



In a **nuclear reactor**, the chain reaction is controlled by **control rods** and the **moderator**. **Control rods** absorb neutrons. This will allow the reactor to produce energy at a steady rate. In a controlled chain reaction, on average only one neutron from each fission will strike another nucleus and cause further stimulated fission to occur. In an uncontrolled chain reaction all the neutrons from each fission strike other nuclei producing a large surge of energy. This occurs in atomic bombs.

3. **Containment Vessel:** A very thick shield of steel and concrete is required to prevent any escape of neutrons or radioactive fragments.



MAN-MADE NUCLEAR FUSION

On Earth, attempts have been made to create nuclear fusion reactors for use in electrical power generation but the technology to achieve the extremely high temperatures and pressures is very expensive and difficult to create.

Compared to nuclear fission, nuclear fusion reactors:

- Release even more energy per kg of fuel

- Make less radioactive emissions as many of the products are stable (e.g. ${}^{4}_{2}He$)
- Use 'cleaner' fuel: isotopes of hydrogen, which can be made from water and lithium