

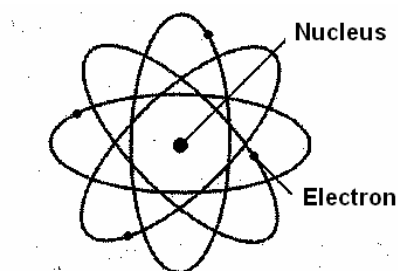
CHAPTER 10: RADIOACTIVITY

10

10.1 Atom Basics

10.1.1 Atom structure

- An atom consists of a small central **nucleus** surrounded by moving **electrons**.
- The particles within a nucleus are known as nucleons:
 - **Protons**
 - **Neutrons**



- An element X can be represented by:



where Z = number of **protons** in the nucleus of element X
 A = number of **nucleons** in the nucleus of element X
 $= Z + N$ where N = number of **neutrons**

Fundamental particle	Symbol	Actual mass	Relative mass	Charge
Proton, p	${}^1_1 p$	1.67×10^{-27} kg	1	$+1.6 \times 10^{-19}$ C
Neutron, n	${}^1_0 n$	1.67×10^{-27} kg	1	0
Electron, e	${}^0_{-1} e$	9.11×10^{-31} kg	$\frac{1}{1840}$	-1.6×10^{-19} C

10.1.2 Radioisotopes

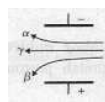
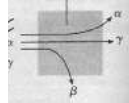
- Isotopes are atoms of an element which have the same number of protons but **different number of nucleons**
- Radioisotopes are isotopes with unstable nuclei
- Atoms with a large number nucleons have a higher probability of having unstable nuclei

10.1.3 Radioactivity

- **Radioactivity** is the process of decay of an unstable nucleus that transmits radioactive radiation to achieve a more stable configuration
- There are three types of radioactive rays:
 - Alpha particles (α)
 - Beta particles (β)
 - Gamma rays (γ)
- A radioactive source can transmit more than one type of radioactive ray

	Alpha particles (α)	Beta particles (β)	Gamma rays (γ)
Composition	Helium nucleus	High-velocity electrons	High frequency electromagnetic waves
Symbol	${}^4_2\text{He}$	${}^0_{-1}e$	-
Charge	$+2e$ $+2 \times (1.6 \times 10^{-19} \text{ C})$	$-e$ $-1.6 \times 10^{-19} \text{ C}$	No charge
Mass	Large	Very small	No mass
Velocity	Approximately 10% of the speed of light	Approximately 90% of the speed of light	Equivalent to the speed of light

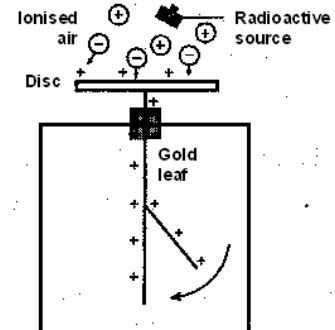
- Radioactive rays can ionise the atoms of a material
- Ionisation is the removal of one or more electrons from an atom or molecule
- After collision, a pair of ions will be formed:
 - **Negative ion:** discarded electron
 - **Positive ion:** the molecule with missing electron(s)

Characteristic	α particle	β particle	γ particle
Ionization potential	Greatest	Less than α	Least
Penetration	Lowest	Greater than α	Largest
Range in air	Several centimeters	Several meters	Several hundred meters
Stopped by	Thin paper or human skin	Several millimeters of aluminum	Several centimeters of plumbum(lead) or several meters of concrete
Electric field	γ -rays remain undeflected since it is uncharged β -rays experience a large deflection due to its small mass 		
Magnetic field	The direction of deflection can be determined with Fleming's Left Hand Rule 		

10.2 Radioactive Detectors

10.2.1 Electroscope

1. The electroscope is positively charged.
2. An alpha source is placed near the electroscope disc.
3. The deflection of the gold leaf will decrease.



Working Principle

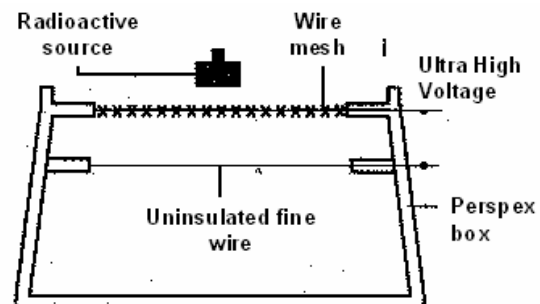
1. The alpha particles will ionise the surrounding air molecules and ionic pairs will be created.
2. The charged electroscope will attract the negative ions and the electroscope will discharge.

Detects:

- Alpha
- Beta (but takes a very long time)

10.2.2 Spark Counter

1. The potential difference for the ultra high voltage is increased slowly until sparks are produced.
2. The potential difference is then decreased just to the point where there are no more sparks.
3. The alpha radioactive source is brought close to the wire mesh.
4. When the source is far from the wire mesh, there are **no** sparks; when the source is near the wire mesh, sparks are seen and heard.



Working Principle

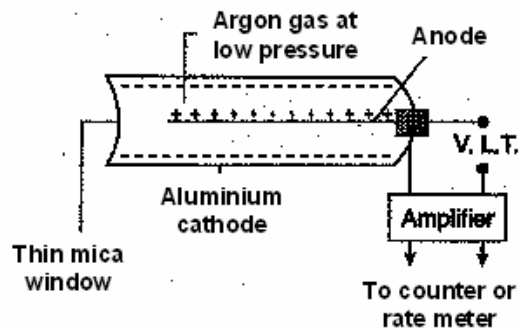
1. Alpha particles have short ranges in air.
2. The alpha particles will ionise the air molecules between the wire mesh and the fine wire.
3. The positive and negative ions will be attracted to their respective terminals, and the movement in opposite directions will cause collisions that generate sparks.
4. The random generation of sparks prove that radioactivity is a random process.

Detects:

- Alpha

10.2.3 Geiger-Muller Tube (GM-Tube)

1. The GM-tube is a very sensitive detector.
2. The mica window is thin to allow the alpha particles (which have low penetration) to penetrate the window.
3. Gamma rays (which have high penetration) penetrate the GM-tube via the mica window and the tube walls.



Working Principle

1. The rays entering the tube will ionise the argon atoms to create positive and negative ions.
2. The electrons which accelerate towards the anode will gather enough energy to create additional ions from other molecules; therefore a chain reaction will ensue and a large number of electrons will be attracted to the anode.
3. All the electrons collected by the anode will create one **current pulse**. This current impulse will be amplified and sent to the **scaler or ratemeter**.
4. The scaler will count the number of pulses in certain period of time.
5. The ratemeter will display the rate of pulses (i.e. pulses per minute or per second)

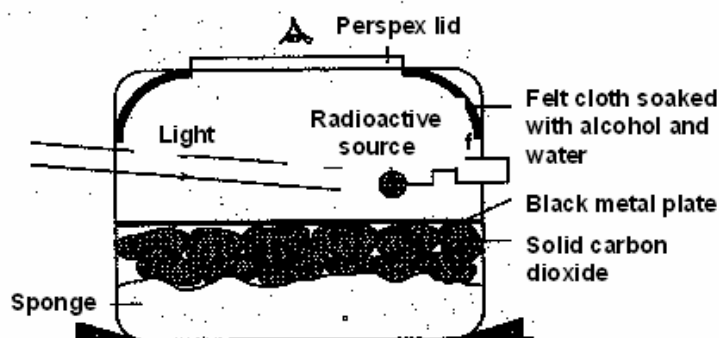
Background Radiation

- When the GM-tube and scaler is switched on, a random counter will still be recorded even without a radioactive source. This is due to **background radiation**.
- Background radiation comes from natural sources such as rocks, soil, air, building materials, food and drink – and even space.
- Background radiation must be taken into account when using the reading taken from the GM-tube

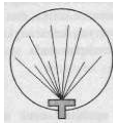
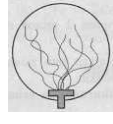
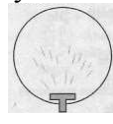
Detects:

- Alpha
- Beta
- Gamma

10.2.4 Cloud Chamber

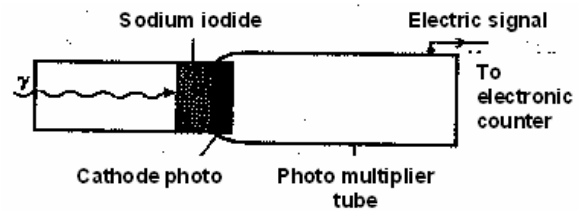


Component	Function
Sponge	Presses the dry carbon so that it touches the metal base
Metal base painted black	The base is cooled by dry carbon and this subsequently cools the air above it. The black color provides a dark background which enables the vapor trails to be seen clearly.
Felt cloth that is soaked in water alcohol-water mixture.	Water and alcohol droplets will evaporate
Perspex cover	After rubbed, the cover will be charged and attract ions in the chamber. In this way the old trails are eliminated and new trails can be observed clearly.

Trail	Property of trails	Explanation
Alpha particles 	Thick	- Greatest ionization - Many ion pairs produced - Many alcohol droplets condenses on ions
	Thin	Alpha particles have relatively large mass and hence does not deflect easily due to collisions with air molecules
	Approximately of same length	All alpha particles have approximately the same energy
Beta particles 	Fine	- Low ionization potential - Not many ion pairs produced
	Curved	Beta particles have extremely small mass and hence are easily deflected by collision with air molecules
	Unequal length	Beta particles have different energies
Gamma rays 	Short and extremely fine	Lowest ionization potential
	Scattered and rare	Few ion pairs produced.

10.2.5 Scintillation Chamber

1. When radioactive radiation passes through sodium iodide crystals, energy is absorbed producing **visible light**.
2. This light results in the emission of **electrons** from the **photo-cathode**.
3. Electrons are detected and multiplied by a **photo-multiplier tube** which results in an **electric signal**.
4. This electric signal is amplified by an amplifier.
5. Subsequently, the electric signals are collected and counted by an **electronic counter**.
6. The scintillation counter operates quickly and efficiently.



Detects:

- Alpha
- Beta
- Gamma
- All types of radiation including X-rays

10.2.6 Photographic Plate

1. A photographic plate coated with argentic bromide is sensitive to light and radioactive radiation.
2. When exposed to light or radioactive radiation, the argentic element will darken the plate after processing.
3. The degree of darkening depends on the strength of the radiation received.
4. Photographic plates are used in the safety badges worn by personnel working in high-risk areas involving radioactive radiation.

Detects:

- Alpha
- Beta
- Gamma
- All types of radiation including light

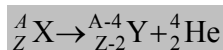
10.3 Radioactive Decay

10.3.1 Radioactive Decay

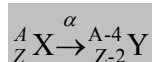
- Radioactive decay is the process of emission of radioactive radiation from unstable nuclei to achieve a more stable configuration
- Radioactive decay is a spontaneous process which:
 - occurs independently
 - cannot be controlled
 - is not influenced by physical quantities such as temperature and pressure
 - is not influenced by the chemical composition of the radioactive substance
 - cannot be slowed down or stopped completely.
- Radioactive decay is a random process, i.e.
 - There is no method to determine which atom will began decaying at a given time
 - All atoms have the same probability of decaying at any given time

Alpha decay

- Alpha decay happens when a radioactive element decays by emitting **alpha particles** (${}^4_2\text{He}$)
- Alpha particles consist of 2 protons and 2 neutrons
- A nucleus which emits one alpha particle will have:
 - Reduction of number of protons by **two**
 - Reduction of number of nucleons by **four**



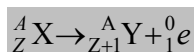
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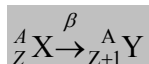
Beta decay

- Beta decay happens when a radioactive element emits beta particles (${}^0_{-1}e$)
- A neutron will split into one proton and one electron

$${}^1_0n \rightarrow {}^1_1p + {}^0_{-1}e$$
- The proton will remain in the nucleus and the electron is ejected at high speed
- A nucleus which emits one beta particle will have:
 - Increase of number of protons by **one**
 - Unchanged number of neutrons

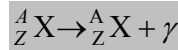


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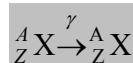


Gamma decay

- Gamma decay happens when a radioactive nucleus releases its excess energy in the form of **high frequency electromagnetic waves**.
- There are no changes in the number of protons and nucleons but the total energy of the radioactive nucleus will decrease.



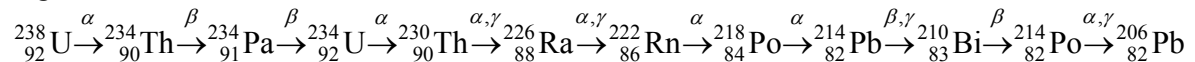
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10.3.2 Decay Series

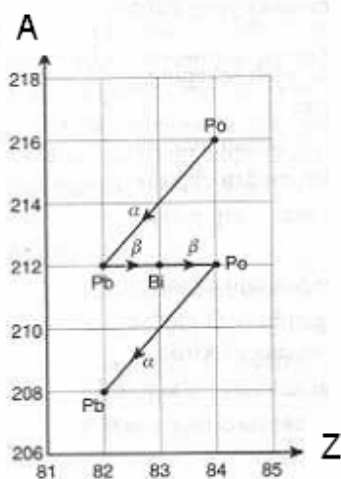
- Some nuclei are still unstable after one decay; the new nuclei are still radioactive and will continue decay.
- A series of decay will happen until a more stable nucleus is obtained.

E.g.:

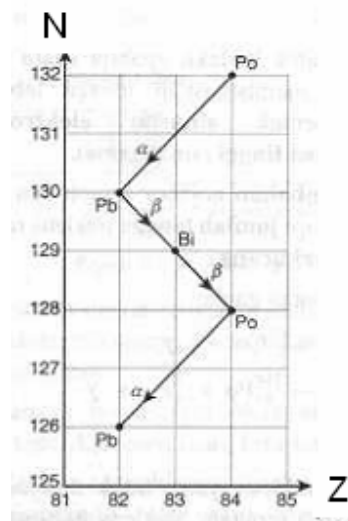


- A decay series can be shown with:

Graph of A against Z



Graph of N against Z



A: Number of nucleons
N: Number of neutrons
Z: Number of protons

10.4 Half-Life

- The nuclei in a radioactive sample will decay at different times because radioactivity is a random process
- Because a radioactive sample contains a huge number of radioactive nuclei, radioactive decay will occur all the time
- The activity of a radioactive sample is the rate of decay of a radioactive sample
Rate of decay = number of decays per second
= number of particles emitted per second
- Different radioactive elements decay at different rates
- The rate of decay is directly proportionate to the number of radioactive atoms
- The half-life of a radioactive element is the time taken for its activity to decrease to half its original value
- In the time of one half-life:
 - The activity is halved
 - The number of active atoms is halved
 - The rate of radiation emission is halved

Radioisotope	Symbol	Half-life
Radon-220	$^{220}_{86}\text{Rn}$	56 seconds
Technetium-99m	$^{99}_{43}\text{Tc}$	6 hours
Sodium-24	$^{24}_{11}\text{Na}$	15 hours
Iodine-131	$^{131}_{53}\text{I}$	8 days
Phosphorus-32	$^{32}_{15}\text{P}$	15 days
Radium-226	$^{226}_{88}\text{Ra}$	1620 years
Carbon-14	$^{14}_6\text{C}$	5730 years
Uranium-238	$^{238}_{92}\text{U}$	4500 million years

10.4.1 Application

- Different radioisotopes have different half-lives. A radioisotope can be identified by measuring its half-life
- A radioactive element used in medicine should have **short** half-lives
- Radioactive elements with long half-lives will maintain its high level of activity for a long period of time

Example:

- Medicine: technetium-99m (half-life: 6 hours) injected in blood stream to detect brain cancer, internal hemorrhage, and blood clots
- Radioactive labs: Radioactive samples with long half-lives so that they do not have to be replaced often. E.g. strontium-90 for beta rays (half-life: 28.5 years)
- Smoke detectors: americium-241 (half-life: 432 years) used in buildings for minimum maintenance

10.4.2 Archeology

- Carbon-14 is used to determine the age of ancient artifacts
- Neutrons in the cosmic radiation collide with nitrogen in the atmosphere, creating C-14
- This causes a small part of the carbon atoms in CO₂ to exist as C-14
- Living beings will always continue absorbing C-14
- When a living thing dies, C-14 will no longer be absorbed. Therefore the old C-14 will decay and its activity decreases
- When an ancient artifact is found, the activity of 1g C of that object is compared to 1g C of a current object
- Half-life of C-14 is 5730 years

10.4.3 Medicine

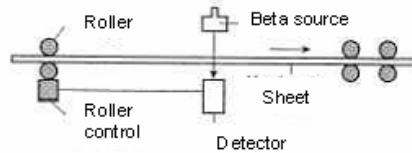
- Cobalt-60: kill cancer cells in radiotherapy
- Gamma: sterilization
- Sodium-24: to detect blood clot
- Phosphorus-32: to detect brain tumour
- Iodine-131: to determine thyroid glands
- Iron-59: to trace iron distribution in blood

10.4.4 Agriculture

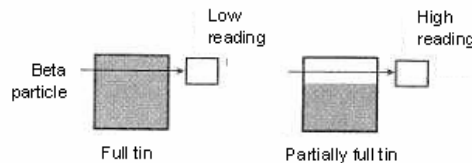
- The rate and quantity of fertilizer absorption by plants can be determined by mixing radioactive phosphate into the fertilizer. The plants can be tested thereafter with a GM-tube
- Radioactive radiation from radioisotopes are used to kill pests
- Pests can also be multiplied in the lab and exposed to gamma rays, where they will mutate to infertility

10.4.5 Industry

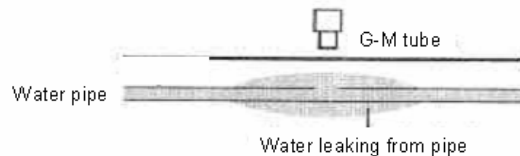
- Automatic thickness control of paper, plastic and metal sheets



- Automatic check of level of fullness within tins and packages



- Salt containing sodium-24 is dissolved in a water tank and used to detect underground pipe leakage



- Synthetic cloths are discharged during manufacturing using strong alpha sources
- Gamma rays with high penetration are used to detect internal cracks within a steel plate

10.5 Nuclear Energy

- In a nuclear reaction or radioactive decay, the total mass of particles created are less than the original particle mass
- The nuclear reaction or radioactive decay involves a **loss in mass** or **mass defects**
- The deficient mass has been converted to **energy**

Einstein's law of energy-mass conservation:

$$E = mc^2$$

where E = total energy released [J]

m = mass defect [kg]

c = speed of light = $3 \times 10^8 \text{ m s}^{-2}$

10.5.1 Atomic Mass Units

In a nuclear reaction or radioactive decay, the particle mass is usually measured in **atomic mass units (a.m.u.)**

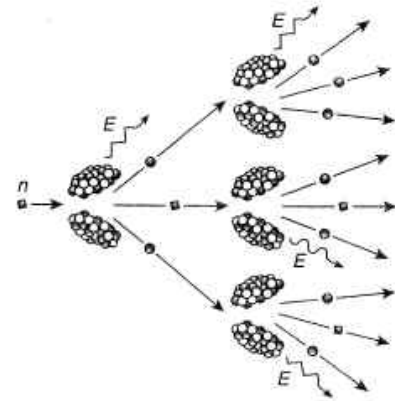
$$\begin{aligned} 1 \text{ a.m.u.} &\equiv \frac{1}{12} \text{ mass of } {}^{12}_6\text{C} \\ &= \frac{1}{12} \times 1.993 \times 10^{-26} \text{ kg} \\ &= 1.66 \times 10^{-27} \text{ kg} \end{aligned}$$

10.5.2 Nuclear Fission

- Nuclear fission is the process of splitting a massive nucleus into two or more lighter nuclei accompanied by the copious release of energy
- The light nuclei have almost similar masses
- Fission usually occurs when a neutron collides with a massive nucleus
- Nuclear fission results in a mass defect which is converted into kinetic energy
- When the resultant nuclei collide with surrounding atoms, the kinetic energy is converted to heat energy
- A uranium-235 nucleus collided with a neutron will split into two large nuclei and three new neutrons

Chain Reaction

- The additional neutrons as a result of nuclear fission are known as **fission neutrons**
- Part of the fission neutrons will escape from the surface of the radioactive sample
- The remaining fission neutrons will catalyze more nuclear fissions
- This causes a **chain reaction**
- Chain reactions can only happen if the mass of the uranium sample exceeds a minimum amount known as **critical mass**

**Note:**

A spherically shaped uranium sample will have lower critical masses than other shaped samples because for a given volume, spheres have lower surface areas, which reduces the likelihood of escaped fission neutrons

10.5.3 Nuclear Fusion

- Nuclear fusion occurs when two light nuclei combine to form a heavier nucleus
- The fusion of two hydrogen isotopes are as follows:

$${}^2_1\text{H} + {}^3_1\text{H} \rightarrow {}^4_2\text{He} + {}^1_0\text{n} + \text{energy}$$
- Fusion occurs at extremely high temperatures so that the light nuclei possess sufficient kinetic energy to overcome the electrostatic repulsion
- Fusion reactions occur frequently on the surface of the sun due to the copious amounts of hydrogen gas and high temperature

10.6 Radioactive Waste Management

- Radioactive wastes are the remnant isotopes after a radioactive reaction or decay
- Radioactive wastes contain radioactive substances that emit radiation which are harmful to humans
- Radioactive wastes usually have long half-lives and strong radiation emissions; therefore efficient management is necessary to minimize exposure and contamination
- Determining how to handle radioactive wastes depends on:
 - The half-lives of the radioisotopes
 - The concentration of the radioactive waste
 - The heat emitted from the radioactive waste
- There are three classifications of radioactive wastes based on their concentration, i.e.
 - Low-grade radioactive waste
 - Medium-grade radioactive waste
 - High-grade radioactive waste

10.6.1 Low-grade radioactive waste

- Originates from hospitals, industries, and nuclear labs
- Consists of contaminated utensils, clothing, and bandages
- Solids are stored in special drums and buried underground
- Liquids (coolant fluid from nuclear power stations) are deposited into the sea via long pipes and released 1-2km from coastline
- Gases are released into the atmosphere

10.6.2 Medium-grade radioactive waste

- Mostly originates from nuclear power stations
- Stored in special drums, encased in concrete blocks, and buried underground or in used mines

10.6.3 High-grade radioactive waste

- Consists of **spent fuel rods** from nuclear reactors which are still radioactive and hot
- Stored in pools of water for several years to cool, and then stored in steel containers and buried approx. 500m underground
- The fuel rods can also be **reprocessed** and **enriched** for reuse

10.7 Negative Effects

10.7.1 Negative effects

- Overexposure will cause:
 - Death of living organisms, or
 - Mutation of surviving cells
- The severity of the effects depend on the distance from the radioactive source and the strength of penetration of radiation
- The effects of exposure to radiation for humans can be categorised as:
 - Somatic
 - Damage to the body except reproductive cells
 - Symptoms such as fatigue, nausea, loss of hair and skin lesions
 - Delayed effects such as cataracts and leukemia
 - Genetic
 - Damage to reproductive cells
 - Dangerous cell mutations which might be transferred to future generations

10.7.2 Safety precautions

- Storage places and containers labeled accordingly
- Weak sources handled using tongs
- Strong sources handled using remote controls through plumbum glass screens
- Thick plumbum shields installed between radioactive sources and workers
- Protective suits and gloves worn at all times. A film badge sensitive to radiation to be worn to monitor the radiation exposure
- Food and drink banned altogether
- Wastes stored or disposed using proper methods



10.8 Alternative Power Sources

- With the depleting natural sources such as petroleum and charcoal, alternative power sources are necessary
- Petroleum is needed in large quantities as the main power source for transportation
- However, large quantities of petroleum is subject to pollution during transportation; any spills will be difficult to manage
- Petroleum and charcoal also produce **byproducts** such as carbon dioxide, sulphur dioxide, and carbon monoxide with pollute nature

10.8.1 Benefits of nuclear energy

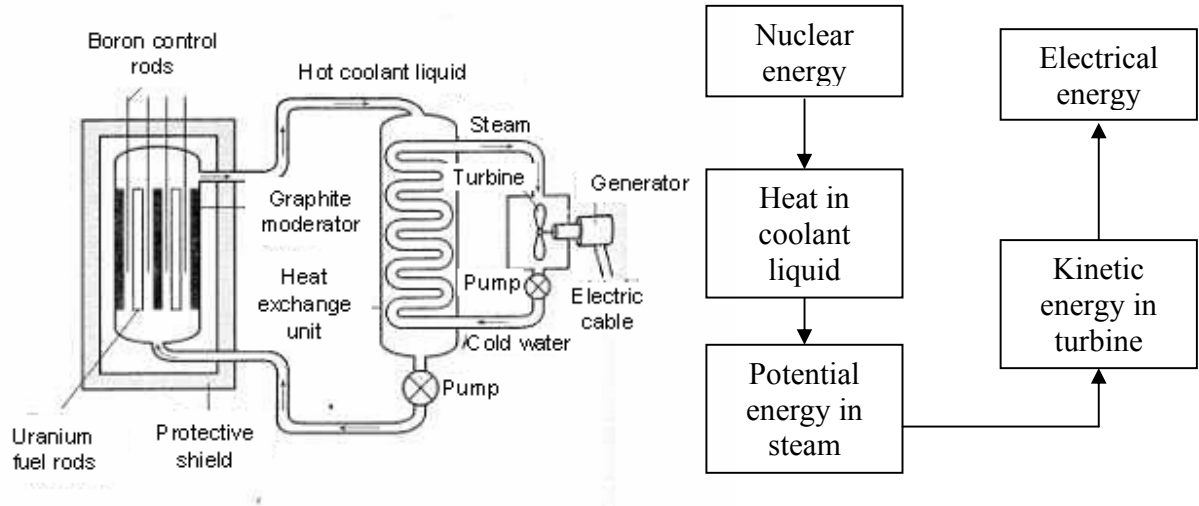
- Small quantities produce huge amounts of energy
- No polluting byproducts
- Natural nuclear sources (e.g. uranium) still exist in large amounts
- Nuclear reactors producing nuclear energy can also be used to generate radioisotopes for use in industries, medicine, agriculture and research fields.
- Nuclear energy generation is a clean and safe process if safety rules are adhered to. Accidents at Three Mile Island and Chernobyl are isolated cases due to human negligence

10.8.2 Disadvantages of nuclear energy

- Nuclear energy is non-renewable. Uranium supply is limited and can only be found in certain countries
- Nuclear power stations produce **radioactive wastes** that have **long half-lives** and are **difficult to dispose off**.
- Radioactive rays from the reactor can leak out to the environment and endanger lives
- Nuclear power stations have a non-negligible risk of mishap which could result in widespread environmental contamination persisting for several generations.

10.8.3 Nuclear reactors

Nuclear energy is generated by nuclear fission generators



Component	Description
Fuel rod	A long rod that has trace amounts of enriched uranium-235. Nuclear reactions occur within these rods when the uranium nuclei undergo fission due to continuous neutron bombardment.
Control rod	Boron or cadmium rod. Absorbs excess neutrons so that the rate of chain reactions can be controlled.
Graphite moderator	Slows down the fission neutrons. Neutrons with low kinetic energy can be easily captured by the uranium nucleus to initiate the fission process.
Coolant	Liquid sodium, water, heavy water (water molecule but with the isotope) or carbon dioxide gas which have large specific heat capacity. The heat generated from the reactor core is transferred to the heat exchange unit.
Heat exchange unit	Heat is transferred via piping that contains water. The water in these pipes boil and undergo transition to the gas state. The flow of steam rotates the turbine which then drives the generator to generate electricity.
Radiation shield	A 2 m thick wall of solid concrete, steel, graphite and lead. Ensures the gamma rays and neutrons do not escape from the reactor core.