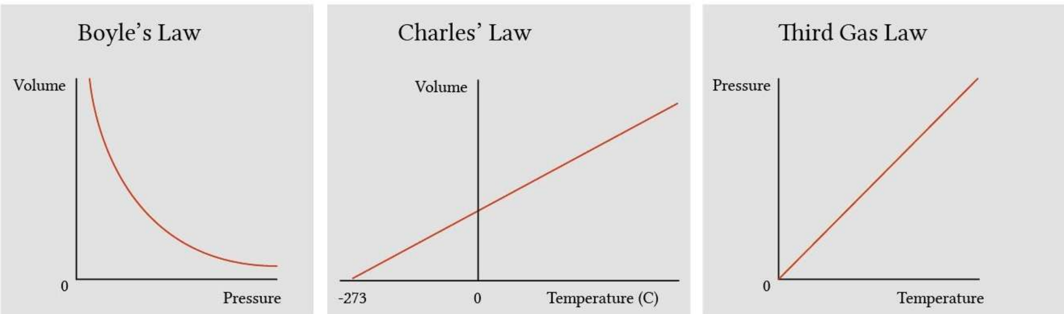
3.6.2 Thermal physics

3.6.2.1 Thermal energy transfer

- Internal energy
  - The sum of randomly distributed KE and PE **of the particles** in a body
  - Symbol = U
  - Unit = J
  - For an ideal gas, **its internal energy is equivalent to the sum of the kinetic energy of its gas particles**
- The first law of thermodynamics
  - The change of internal energy of the object = the total energy transfer due to work done and heating
  - $\Delta U = \Delta Q + \Delta W$
- Specific heat capacity / c
  - The amount of energy needed to raise the temperature of 1 kg of the substance by 1 K **without change of state**
  - Unit = J kg^{-1} K^{-1}
  - $\Delta Q = mc\Delta\theta$
- Latent heat
  - During a change of state, the PE of particles are changing but not KE
  - The temperature of the substance does not change
  - Energy to change state: $Q = ml = \text{mass} \times \text{specific latent heat}$
- Specific latent heat of fusion / l_f
  - The amount of energy needed to change the state of 1 kg of the substance from solid to liquid **without a change of temperature**
  - Unit = J kg^{-1}
- Specific latent heat of vapourisation
  - The amount of energy needed to change the state of 1 kg of the substance from liquid to gas **without a change of temperature**
  - Generally much higher than specific latent heat of fusion for a substance
  - Unit = J kg^{-1}
- Continuous flow heating
  - $P = \frac{\Delta \text{Q}}{\text{t}} = mc\frac{\Delta\theta}{t}$

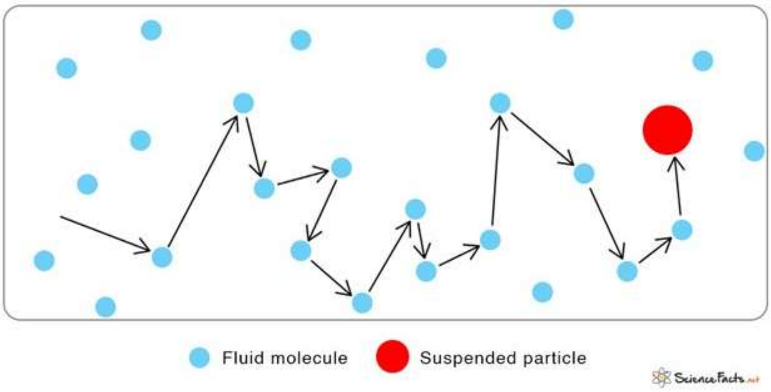
3.6.2.2 Ideal gases

- Experimental gas laws
  - In a **closed system**
  - Boyle's Law: constant T, $p \propto \frac{1}{V}$ / $p_1V_1 = p_2V_2$
  - Gay-Lussac's Law: constant V, $p \propto T$ / $\frac{p_1}{T_1} = \frac{p_2}{T_2}$
  - Charles' Law: constant P, $V \propto T$ / $\frac{V_1}{T_1} = \frac{V_2}{T_2}$
  - Rearranging ideal gas equation: $\frac{p_1v_1}{T_1} = \frac{p_2v_2}{T_2}$
  - 

  - Break down at very high pressures and very low temperatures

        - Molecules become so close that their own volume becomes significant and intermolecular forces become significant
- Avogadro's Law
    - $V \propto N$
    - $\frac{V_1}{N_1} = \frac{V_2}{N_2}$
    - Equal volumes of gas at the same temperature and pressure contains the same number of molecules (N)
- Ideal gas equation
    - $pV \propto T$
    - In moles: $pV = nRT$
        - n = number of moles of gas
        - R = molar gas constant = 8.134 J kg^{-1} mol^{-1}
    - In number of molecules: $pV = NkT$
        - N = number of molecules of gas
        - k = Boltzmann constant = 1.38×10^{-23} J K^{-1} = $\frac{R}{N_A}$
- Density of a gas
    - $\rho = \frac{pM}{RT}$
    - Shown by using $M_s = \frac{pVM}{RT}$ and $\rho = \frac{M_s}{V}$
- Work done by the gas on a piston
    - $\text{Work done} = p\Delta v = \text{pressure} \times \text{change in volume}$
- Absolute zero
    - $\text{Temperature} = 0\ \text{K} = -273.15\ °\text{C}$
    - Extrapolate the graph of Charles' Law / Pressure Law → 0 pressure and volume at absolute zero
    - The temperature at which motion stops and KE of particles is 0

3.6.2.3 Molecular kinetic theory model

- Brownian motion
    - The observed **random and unpredictable** motion of small particles suspended in a liquid or gas
    - Particles have a range of speeds and no preferred direction of movement
    - A result of collisions with fast, randomly moving particles in the fluid
    - The particles in the fluid transferred momentum to the larger particles suspended when they collide
    - Provided evidence for existence of atoms
    - 

- Explanation of gas laws
    - Boyle's Law
        - The pressure of a gas at constant temperature is increased by reducing its volume
        - The gas molecules travel less distance between impacts at the walls when volume is reduced
        - There are more impacts per second so the force exerted is greater (rate of change of momentum for particles faster; Newton's 3rd Law) and pressure is greater
    - The pressure law / Gay-Lussac's Law

    - The pressure of a gas at constant volume is increased by raising its temperature
    - The average speed of the molecules increase due to increasing temperature
    - The impacts of the molecules on the container walls are harder and more frequent
    - Force exerted is greater (rate of change of momentum for particles faster; Newton's 3rd Law) so pressure increases
  - Charles' Law
    - Volume is directly proportional to temperature at constant pressure
    - When the temperature of a gas is increased, its molecules gain kinetic energy meaning they will move more quickly
    - Because pressure is kept constant (therefore frequency of collisions is constant) the molecules move further apart and volume is increased.
- The kinetic theory
  - root mean square speed, $c_{\text{rms}} = \left[\frac{c_1^2 + c_2^2 + \cdots + c_N^2}{N}\right]^{\frac{1}{2}}$
  - $pV = \frac{1}{3}Nm(c_{\text{rms}})^2$
    - m = mass per molecule
    - N = number of identical molecules
- Difference between gas laws and kinetic theory
  - Gas laws are empirical
    - They have experimental observation and evidence
  - Kinetic theory are theories
    - They are based on assumptions and derivations
- Assumptions for kinetic theory
  - Molecules are point like (negligible volume)
  - Molecules do not attract each other (negligible intermolecular forces)
  - The molecules are in continual random motion
  - The molecules collide elastically with each other and the container
  - The duration of collisions is negligible in comparison to time between collisions
- Derivation of the kinetic theory equation
  - Consider walls in one direction first (x)
  - Time between collision with a wall and back is $t = \frac{2l_x}{u_1}$
  - $F_{1\,molecule} = \frac{\Delta p}{t} = -\frac{2mu_1}{\frac{2l_x}{u_1}} = -\frac{mu_1^2}{l_x}$
  - $p_1 = \frac{F_{1\,wall}}{A} = \frac{F_{1\,wall}}{l_y l_z} = \frac{mu_1^2}{l_x l_y l_z} = \frac{mu_1^2}{V}$
  - $p = \sum_{n=1}^{N} p_n = \sum_{n=1}^{N} \frac{mu_n^2}{V} = \frac{Nm}{V} \times \frac{1}{N}\sum_{n=1}^{N} u_i^2 = \frac{Nm}{V}\overline{u^2}$
  - Similar result is derived for the y and z direction
    - $p = \frac{Nm}{V}\overline{v^2}$ and $p = \frac{Nm}{V}\overline{w^2}$
  - Average pressure = average pressure on walls
    - $p = \frac{Nm}{V} \times \frac{1}{3}\left(\overline{u^2} + \overline{v^2} + \overline{w^2}\right) = \frac{1}{3} \times \frac{Nm}{V} \times (c_{rms})^2$
- Internal energy of gases
  - $U = \Sigma$ kinetic energy $+ \Sigma$ potential energy
  - For ideal gas there is no intermolecular forces so potential energy = 0 and $U = \Sigma$ kinetic energy
  - Mean kinetic energy of a molecule of an ideal gas
    - $E_{\text{K}} = \frac{1}{2}m(c_{\text{rms}})^2 = \frac{3pV}{2N} = \frac{3}{2}kT = \frac{3RT}{2N_A}$
    - m = mass per molecule
  - Total internal energy of n moles of ideal gas

- internal energy $= \frac{3}{2}nRT$

3.7.1 Fields

3.7.1 Fields

- Force field
  - A region in which a body experiences a non-contact force
  - Arise from the interaction of mass / static charge / between moving charges
  - Can be represented as a vector (direction needs to be determined by inspection) or as field lines
- Gravitational force vs. electrostatic force

Property	Gravitational fields	Electric fields
Origin	Produced by and act upon masses	Produced by and act upon charges
Factors affecting size	Directional proportional to product of masses +inversely proportional to square of distance	Directional proportional to product of charges + inversely proportional to square of distance
Effect	Attraction only	Attraction or repulsion
Shielding	Not possible	Possible e.g. Faraday cages
Comparative sizes	Insignificant unless one of the masses is huge	Many orders of magnitude bigger
Potential	Potential = work per unit mass	Potential = work per unit charge
Gradient of potential with respect to distance	Field strength	Field strength

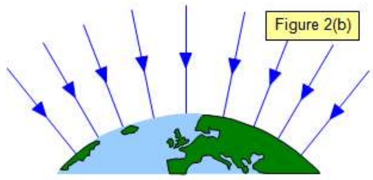
- Relative size
  - Electrostatic force is often many orders of magnitude stronger

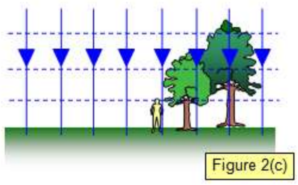
3.7.2 Gravitational fields

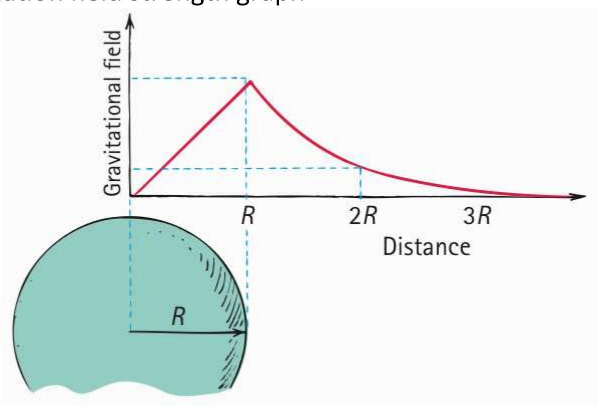
3.7.2.1 Newton's law

- Gravitational force
    - A universal attractive force acting between all matter with mass
- Newton's Law of Gravitation
    - The attractive force between 2 particles / point masses is proportional to the product of masses and inversely proportional to the square of separation / distance
    - $F = \frac{Gm_1m_2}{r^2}$
    - $G = 6.67 \times 10^{-11}\ \mathrm{N\ m^2\ kg^{-2}}$

3.7.2.2 Gravitational field strength

- Gravitational field lines
    - Show the **direction** and relative magnitude of the **force** on a **mass** placed in the gravitational field
- Types of field lines
    - Radially pointing towards centre of mass
    - On the surface of the Earth = uniform field
    - 

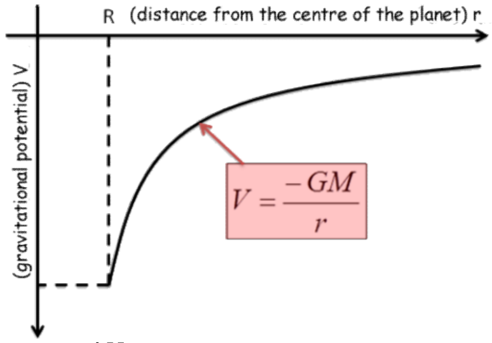


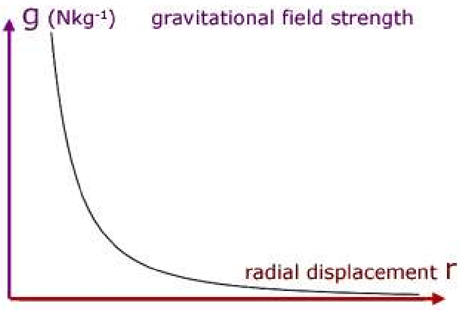
- Gravitational field strength
    - Force per unit mass at a point
    - A **vector quantity** (can have separate x and y values)
    - $g = \frac{F}{m} = \frac{GM}{r^2}$ (in radial field, inverse square relationship)
    - Unit = N kg^{-1}
- Gravitation field strength graph
    - 

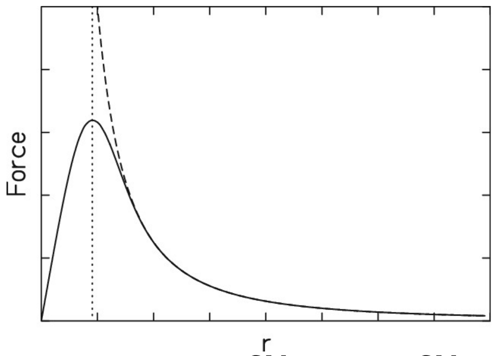
3.7.2.3 Gravitational potential

- Gravitational potential
    - Work done per unit mass in moving a unit mass from infinity to that point
    - A **scalar quantity** (add up gravitational potentials from different gravitational fields directly)
    - Unit = J kg^{-1}
    - Gravitational potential in a radial field: $V = -\frac{GM}{r}$
- Why is gravitational potential always negative
    - Gravitational potential is defined as zero at infinity
    - Gravitational force is attractive so work done on a mass must be increasing to overcome

gravity and reach infinity

- Work done in moving mass
  - $\Delta W = m\Delta V = \text{mass} \times \text{gravitational potential difference}$
- Equipotential surfaces
  - A surface along which the gravitational potential is constant
  - No work is done when moving along equipotential surfaces
  - Field lines are always **perpendicular** to equipotential surfaces
- Graphs
  - V against r
    - 

    - $g = -\frac{\Delta V}{\Delta r}$
  - g against r
    - 

    - Area under graph = ΔV
  - F against r
    - 

    - $\text{GPE} = \int F dr = \int \frac{GMm}{r^2} dr = -\frac{GMm}{r}$
    - This is the total GPE for **both objects** in the field

3.7.2.4 Orbits of planets and satellites

- Kepler's third law
  - $T^2 \propto r^3$
  - $T^2 = \frac{4\pi^2 r^3}{GM}$
  - $\log T = \frac{3}{2}\log r + \frac{1}{2}\log\left(\frac{4\pi^2}{GM}\right)$
- Derivation of Kepler's third law
  1. Circular orbits: $\frac{\text{GMm}}{\text{r}^2} = \frac{\text{mv}^2}{\text{r}}$

2. $v^2 = \frac{GM}{r}$, $v = \sqrt{\frac{GM}{r}}$
3. $\omega = \frac{v}{r} = 2\pi f$
4. $f = \frac{v}{2\pi r}$
5. $T = \frac{2\pi r}{v}$
6. $T = \frac{2\pi r}{\sqrt{\frac{GM}{r}}}$
7. $T^2 = \frac{4\pi^2 r^2}{\frac{GM}{r}} = \frac{4\pi^2 r^3}{GM}$

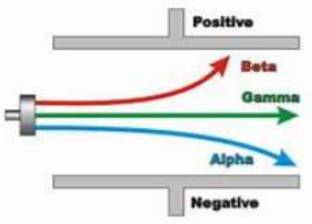
- Energy of a satellite
  - $\text{Total energy of a satellite} = \text{KE} + \text{GPE} = \text{constant} = -\frac{GMm}{2r}$
  - $\text{GPE} = -\frac{GMm}{r}$
  - $\text{KE} = \frac{GMm}{2r}$
  - Conservation of energy: r increases → velocity decreases → KE falls → GPE increases
- Escape velocity
  - The minimum velocity that an object must be given to escape from the planet's gravitational field when projected vertically from the surface
  - $v_{esc} = \sqrt{2gR} = \sqrt{2 \times g \times \text{radius of planet}}$
- Synchronous orbit
  - The time period of the orbiting object = the time period of the rotation of the central orbited object
  - The directions of the orbit is the same as the direction of rotation
- Geostationary orbit
  - Orbiting **in the plane of the equator**
  - Always above the same location on Earth
  - Have the same time period as Earth (24 hours)
  - Move in west-east direction
  - Used by telecommunication satellites
- Low Earth orbits (LEO)
  - Smaller orbital radius, altitude below 2000 km
  - High speed: 90 min time period
  - Used for military and weather monitoring and communication (too fast so several are needed to form a network)
  - Small footprint so they can only see a small part of the surface of Earth
- Middle Earth orbit (MEO)
  - Fly from pole to pole
  - Longer radius than LEO

3.7.3 Electric fields

3.7.3.1 Coulomb's law

- Coulomb's law
  - Force between point charges in a vacuum, $F = \frac{kQ_1Q_2}{r^2} = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r^2}$
  - Force between two point charges is proportional to the product of charges and inversely proportional to the square of distance between the charges
- ε_0 (permittivity of free space)
  - The charge per unit area in C m^{-2} on oppositely charged parallel plates in a vacuum when the electric field strength between the plates is 1 V m^{-2}
  - Value = 8.85×10^{-12} F m^{-1} (Farad per metre)
- Assumptions in calculations
  - Air is not charged so it cannot conduct current
    - Its permittivity is similar to vacuum ($\varepsilon_r = 1.0006$) thus they can be treated is vacuum in calculations
  - For a charged sphere charge may be considered to be at the centre

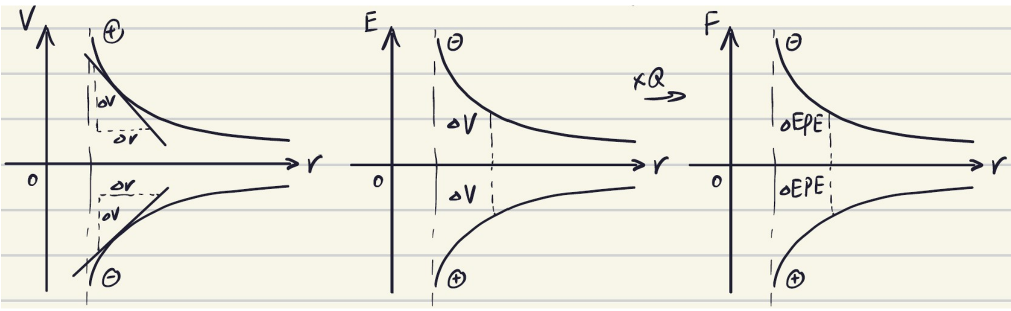
3.7.3.2 Electric field strength

- Electric field strength (E)
  - The electrostatic force **per coulomb of charg**e acting on a **positive** point charge at that point
  - $E = \frac{F}{Q} = \frac{\text{force}}{\text{charge}}$
  - A **vector quantity**
  - Unit = N C^{-1} or V m^{-1}
- Electric field from a point charge
  - Radial field
  - Field lines point outwards = positive charge, inwards = negative charge
  - $E = \frac{Q}{4\pi\varepsilon_0 r_2}$
- Field strength of uniform electric field between 2 plates
  - $E = \frac{V}{d} = \frac{\text{potential difference}}{\text{separation between the two plates}} = \frac{F}{Q}$
- Force on a charge
  - Force on a charge $F = EQ = \text{electrical field strength} \times \text{charge}$
- Deflection of charge
  - Positive charge e.g. alpha particles deflects towards the negative plate
  - Negative charge e.g. beta minus particles deflects towards the positive plate
  - Higher mass = less deflection
  - More charge = more deflection
  - Higher velocity = less deflection
  - 

- Work done for moving charge between plates
  - $W = Fd = Q\Delta V = \text{charge} \times \text{potential difference across the plates}$

3.7.3.3 Electric potential

- Electric potential (V)
  - Work done on a +1C charge to move it from infinity to that point in the field

- 0 at infinity
- Sign of electric potential
  - Charge is positive: potential is positive and the force is repulsive (work done to move)
  - Charge is negative: potential is negative and the force is attractive
- Potential gradient
  - Electric field strength at a point = gradient of electric potential with respect to distance (**not** $\frac{\Delta V}{\Delta d}$ unless it is a straight line)
- Magnitude of electric potential in a radial field
  - $V = \frac{Q}{4\pi\varepsilon_0 r} = \frac{kQ}{r}$
  - Equation also applies to charged spheres (we can take all the charges as acting from the centre)
- Electric potential difference
  - The energy needed to move a unit charge between two points
- Work done in moving charge
  - $\Delta W = Q\Delta V = \text{charge} \times \text{electric potential difference}$
- Equipotential surfaces
  - A surface along which the electric potential is constant
  - No work is done when moving charges along equipotential surfaces
  - Field lines are always **perpendicular** to equipotential surfaces, direction depends on the isolated charge
- Graphs
  - 

  - $E = \frac{\Delta V}{\Delta r}$
  - ΔV = area under E-r graph
  - $\text{EPE} = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r}$

3.7.4 Capacitance

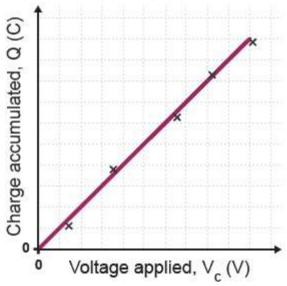
3.7.4.1 Capacitance

- Capacitance (C)
  - Charge stored per unit potential difference across the plates
  - $C = \frac{Q}{V}$
  - Unit = F / Farad (1 F = 1 C V^{-1})
  - Can be rearranged
    - $Q = CV$ i.e. $Q \propto V$

3.7.4.2 Parallel plate capacitor

- Relative permittivity
  - The ratio of the charge stored with the dielectric to the charge stored without the dielectric
  - $\varepsilon_r = \frac{Q}{Q_0} = \frac{C}{C_0} = \frac{\varepsilon}{\varepsilon_0} = \frac{\text{permittivity of material}}{\varepsilon_0}$
  - Aka dielectric constant
- Dielectric
  - Material that increase the capacity of a parallel plate capacitor when placed between the plates
  - $C = \frac{A\varepsilon_0\varepsilon_r}{d} = \frac{\text{surface area of each plate} \times \text{permittivity of free space} \times \text{relative permittivity}}{\text{spacing between the plates}}$
- How does dielectric materials work
  - The molecules are polar in a dielectric / polarised when current applied as electrons got pulled towards positive plate
  - When pd is applied across the plates an electric field is created directing from positive to negative plate
  - Polar molecules align with their positive side facing the negative plate + negative side facing positive plate
  - The aligned molecules produce a counter electric field and reduce the field line between the plates
  - The pd V reduces between the capacitor plates but charge Q remains the same so capacitance increases ($C = \frac{Q}{V}$)

3.7.4.3 Energy stored by a capacitor

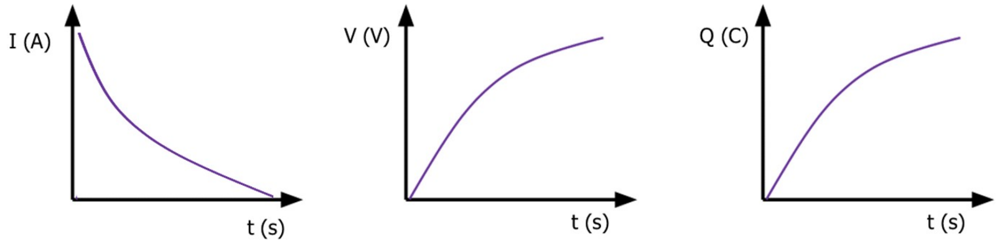
- Graph of charge against voltage
  - 

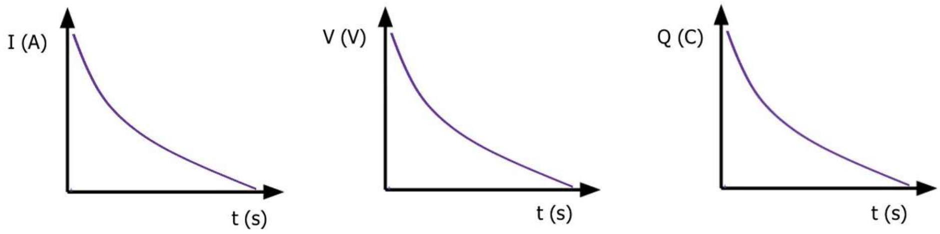
  - Area under = EPE = energy stored by the capacitor
  - $E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2} \times \frac{Q^2}{C}$

3.7.4.4 Capacitor charge and discharge

- Charging a capacitor
  - When pd is connected to the plates, electrons are pushed into the negative plate → repel the electrons in the other plate so it becomes positive → electric field created
  - The charge pushed into the negative plate decreases with time due to the electrostatic

repulsion between electrons on the plate

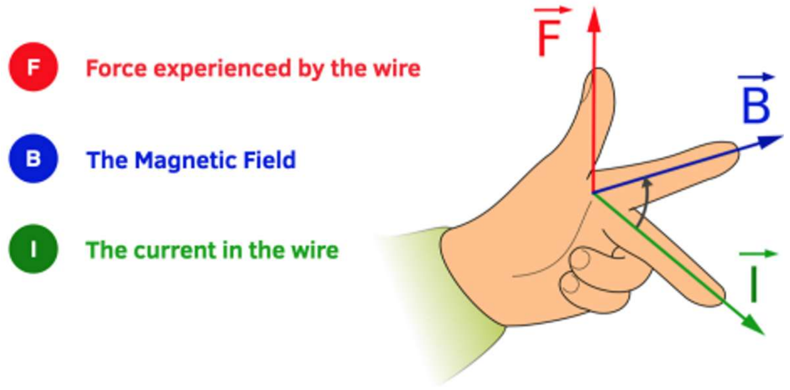
- 

- Discharging capacitors
  - When the capacitor disconnect from the power supply, there is no emf to overcome the repulsive electrostatic force between electrons on the plate
  - The electrons leave and cause pd and current
  - 

- Trend of I, Q and V
  - Q and V always have the same trend because $C = \frac{Q}{V}$ where C is constant
  - The magnitude of I is always decreasing as $I = \frac{dQ}{dt}$ and the rate of charge flowing in or out of the plate is always reducing
- Time constant
  - Time taken for a quantity that decrease exponentially to decrease to $\frac{1}{e}$ of its original value
  - $t = RC = \text{resistance} \times \text{capacitance}$
- Charge at a certain point in time
  - Discharging
    - $Q = Q_0 e^{-\frac{t}{RC}}$
    - $V = V_0 e^{-\frac{t}{RC}}$
    - $I = I_0 e^{-\frac{t}{RC}}$
  - Charging
    - $Q = Q_0\left(1 - e^{-\frac{t}{RC}}\right)$
    - $V = V_0\left(1 - e^{-\frac{t}{RC}}\right)$
    - $I = I_0 e^{-\frac{t}{RC}}$

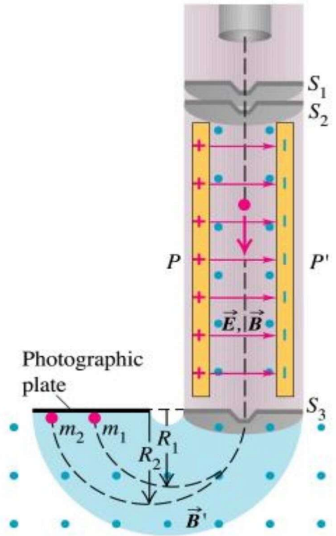
3.7.5 Magnetic fields

3.7.5.1 Magnetic flux density

- Magnetic flux density (B)
  - The magnetic force per unit length per unit current on a current carrying conductor perpendicular to field lines
  - Unit = tesla / T (N m^{-1} A^{-1})
    - 1 tesla = the flux density that produces a force of 1 N in a wire of length 1 m with 1 A flowing perpendicular to the field
- Force on current-carrying wire in a magnetic field
  - Perpendicular: $F = BIL = magnetic\ flux\ density \times current \times length\ of\ wire$
  - At an angle: $F = BIL \sin\theta$
- Fleming's left hand rule
  - 

3.7.5.2 Moving charges in a magnetic field

- Force on a moving charge
  - $F = BQv \sin\theta$
  - Positive charge: thought as the **current direction**
  - Negative charge: thought as the **opposite direction of current**
- Charged particle in circular orbits
  - The velocity of charge is always perpendicular to the field
  - The direction of force on charge is always perpendicular to the direction of travel
  - The force = centripetal force on the charge, charge move in circular path
  - $r = \frac{mv}{BQ}$
- Cyclotron
  - The magnetic field goes into / out of the page → the charged particles move in circular path
  - When particles arrives at the gap the alternating electric field accelerates it through the gap in a straight line so after each half loop the radius will increase
  - When the particle exit through the path on the edge it will be accelerated $2 \times$ the number of loop turns
  - There is a high output velocity
  - speed on exit, $v = \frac{BQR}{m}$
  - $f = \frac{BQ}{2\pi m}, T = \frac{2\pi m}{BQ}$
- Mass spectrometer
  - Measure the relative abundance of ions of various charge to mass ratio
  - Accelerator
    - Has a potential difference
    - Power supply transfers energy to the ion
    - Potential energy of the ion is transferred to the kinetic energy of the ion
  - Velocity selector

- It is essential that all the ions enter the deflector at the same velocity so relative abundance can be measured
  - Electric and magnetic field at right angles to each other
  - Only those with $v = E/B$ won't be deflected ($Bqv = Eq$) and can enter the deflector
- Radius of orbit depends on the specific charge of the particle and can be used to determine specific charge
  - $R = \dfrac{mE}{qB^2}$
- 

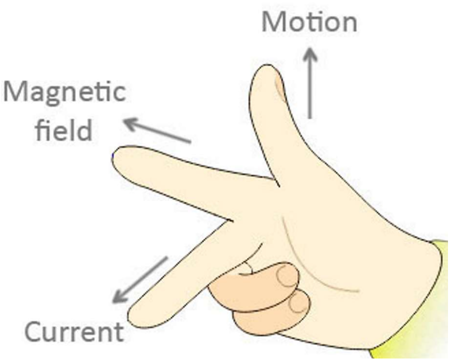
- E/M tube
  - $\dfrac{q}{m} = \dfrac{v}{Br}$

3.7.5.3 Magnetic flux and flux linkage

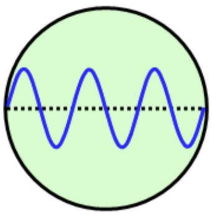
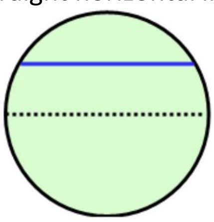
- Magnetic flux
  - $\phi = BA\cos\theta = \text{magnetic flux density} \times \text{area perpendicular to the magnetic field lines}$
  - Can think of it as the number of magnetic field lines through a given area
- Magnetic flux linkage (of a rectangular coil)
  - $N\phi = BAN\cos\theta$ (N = the number of turns cutting the flux)
  - Unit = **Weber (Wb)** = 1 T m^2 = 1 V s

3.7.5.4 Electromagnetic induction

- Faraday's Law
  - The induced emf in a circuit is equal to the rate of change in magnetic flux through the circuit
  - $\varepsilon = -N\dfrac{\Delta\phi}{\Delta t} = -\text{change of flux linkage per second}$
- Faraday's law applications
  - A moving conductor in a magnetic field
    - $\varepsilon = Blv$
  - A fixed coil in a changing magnetic field
    - $\varepsilon = \dfrac{AN\Delta B}{\Delta t}$
  - A rectangular coil moving into a uniform magnetic field
    - $\varepsilon = BNlv$ (only the perpendicular parts matter)
  - A rotating coil
    - $\varepsilon = BAN\omega\sin(\omega t)$
- Lenz's Law
  - When a current is induced by EM induction, the **direction** of the induced current is always such as to **oppose the change that causes (in magnetic flux) the current**
  - Always produce a magnetic field that is **opposite** to the **change** in magnetic field that caused the current
- Lenz's Law experiment

- Moving a magnet into / out of a solenoid with no power supply connected
    - (North side towards the solenoid in this case)
    - Current increase when moving in, north pole induced on the side entering into
    - Current 0 when not moving
    - Current increase but in opposite direction when moving out, south pole induced on the side moving out from
    - $N = 1$ so $\varepsilon = Blv$
- Right hand grip rule
    - Thumb: north pole of solenoid
    - Other fingers curl in the direction of current
- Fleming's right hand rule
    - For **generators**
    - 

3.7.5.5 Alternating currents

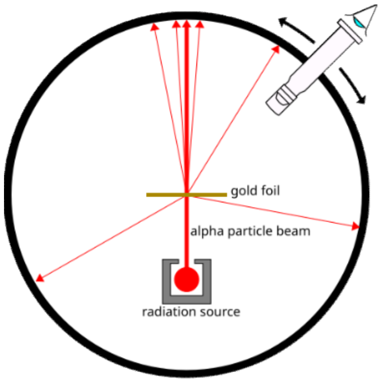
- Alternating currents
    - Periodically varies between a positive value and a negative value over time
    - Sinusoidal: can be described as a sine wave
- Peak current (I_0) / voltage (V_0)
    - The maximum value of current / voltage
    - Peak-to-peak current / voltage = $2I_0$ / $2V_0$
- I_{rms} / V_{rms}
    - The equivalent direct current / voltage that **produces the same power** as the alternating current / voltage
    - $I_{\text{rms}} = \frac{I_0}{\sqrt{2}}$
    - $V_{\text{rms}} = \frac{V_0}{\sqrt{2}}$
- Oscilloscopes
    - AC: transverse wave
        - 
    - DC: straight horizontal line
        - 
    - X-axis: time-base in s cm^{-1} or s div^{-1}
    - Y-axis: y-gain / voltage-gain in V cm^{-1} or V div^{-1}

3.7.5.6 The operation of a transformer

- Transformers
  - Converts the amplitude of an **alternating** pd to a different value
  - Consists of primary coil, secondary coil and a soft iron laminated core
  - (step-up transformer = increases voltage; step-down transformer = decreases voltage)
- How transformers work
  - Current flow in primary coil causes magnetic flux around the coil
  - The current is AC so a changing magnetic field is produced
  - The magnetic flux links the secondary coil
  - The coil increases the magnetic flux linkage from the primary coil to the secondary coil
  - There is change in magnetic flux linkage in the second coil so emf is **induced** in the secondary coil
  - The amplitude of the induced emf is determined by the number of turns in the primary and secondary coil
- Transformer equation
  - $\frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{I_p}{I_s}$
  - Assuming **100% efficiency**
- Efficiency calculation
  - $\text{Efficiency} = \frac{I_s V_s}{I_p V_p}$
- Causes of loss of energy
  - Eddy currents
    - The change in flux caused by the AC creates a magnetic field which acts against the field that induced it (Lenz' Law)
    - This induces a current to flow in the core
  - Resistance of the wire
    - Energy dissipated as heat
  - Power wasted for magnetising and demagnetising the core
- Designs in core to reduce energy waste
  - Soft iron core easily magnetised and demagnetised so less power waster by magnetisation
  - Laminated iron core reduce eddy currents
  - Core made with high resistance to reduce the emf induced and eddy current flowing
- Transmission of electrical power in national grids
  - Aim for high efficiency (minimum power loss)
  - $P = I^2 R$ so the current should be minimised hence the voltage should be maximised
  - Power output from a generator is constant so a step-up transformer is used to increase voltage and decrease current
  - If voltage is too low then current is high and a lot of power is waster
  - If voltage is too high then it might be difficult to insulate the wire

3.8.1 Radioactivity

3.8.1.1 Rutherford scattering

- Plum pudding model
  - The atom was made up of a sphere of positive charge, with small areas of negative charge evenly distributed throughout
- Rutherford scattering experiment
  - Shooting α particles towards a **thin** gold foil in **vacuum**
    - α particles have a short range in air (3-5 cm) -> vacuum to prevent the alpha particle from being absorbed by gas particles when interacting
    - The α particles must not be absorbed by the foil -> thin foil
  - Expectation with plum pudding model
    - All the α particles go straight through since the charge is too spread out in the plum pudding model to deflect the α particles
  - Unexpected observations were found
    - Most of the α particles go straight through → the atom is mostly empty space
    - Some are slightly diffracted → there are concentrated charges inside atoms (can be positive or negative)
    - A small number are deflected straight back → the charge is positive
  - Conclusion
    - The atom is mostly empty space
    - Atoms has a **positively charged** nucleus which contains **most of the mass** at its centre
  - Lead to the nuclear model of atoms + disproved the plum pudding model
  - 

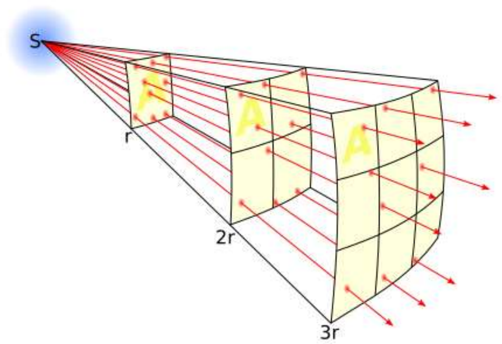
- Nuclear model of atoms
  - All of the positive charge and almost all the mass of the atom is concentrated in the nucleus
  - Electrons orbit the nucleus through empty and is relatively distant from the nucleus
  - No deflection for most alpha particles: too far away from the nucleus to be affected
  - Deflected for a small amount: occasionally an alpha particle pass close to the nucleus

3.8.1.2 α, β and γ radiation

- Radiation properties

	$^{4}_{2}\alpha$	$^{0}_{-1}\beta^{-}$	$^{0}_{0}\gamma$
Range	3-5 cm	0.4-1 m	Infinite
Charge	+2 e	-1 e	None
Ionising ability	Strong	Moderate	Weak
Penetrating ability	Weak	Moderate	Strong
Stopped by	Paper / thin metal foil	About 5 mm of aluminium	Several cm of lead
Type	Particle	Particle	EM radiation (photon)

Deflection in electric fields	Towards negative	Towards positive	**None**
Deflection in magnetic fields	Opposite of β^- Perpendicular to the plane of motion and field lines (use left hand rule)	Opposite of α Perpendicular to the plane of motion and field lines (use left hand rule)	**None**

- Experimental determination of penetrating powers
  - Geiger-muller tube + counter
  - Find background count
  - Place the source of radiation close to the GM tube and measure the count rate
  - Place a sheet of paper between the source and GM rube and measure count rate again
    - If the count rate decreases significantly then the source is emitting alpha radiation
  - Repeat with aluminium foil / several incles of lead
    - Significant decrease in count rate for aluminium foil = beta radiation
    - Significant decrease in count rate for lead = gamma radiation
  - Make sure safety precautions are followed
- Gamma radiation intensity
  - Inverse square law
  - $I = \frac{k}{x^2} = \frac{nhf}{4\pi x^2} = \frac{\text{photons emitted per second} \times \text{energy of each photon}}{4\pi \times \text{distance from source}^2}$
  - 

- Why doesn't inverse square law apply to alpha and beta radiation
  - Gamma radiation is not absorbed when emitted and spreads uniformly from a point source
    - Area over which it spreads is proportional to $\frac{1}{x^2}$
  - Alpha and beta are absorbed in addition to spreading out
- Experimental determination of inverse square law
  - Measuring the count rate of a gamma source at different distances from the GM tube (make sure to adjust for background radiation, specify a range of distances)
  - Plot a graph of corrected count against $\frac{1}{x^2}$
  - Should form a straight line → verify the equation
  - Make sure safety precautions are followed
- Smoke detectors
  - α radiations
  - Alpha radiations ionise air thus conducting current
  - When smoke enters, alpha particles are absorbed thus less current which triggers alarm
  - Short range so people in the room won't be affected
  - Use a source with long half-life so we don't need to frequently replace the source
- Thickness control
  - Beta for paper, gamma for aluminium / metal
  - Measure how much radiation passes through the material
  - Not alpha because it will all be absorbed
  - Beta will be absorbed by metal, gamma is barely affected by paper
- Therapy for cancer
  - Gamma radiations
  - Malignant cancer cells are destroyed by the radiation

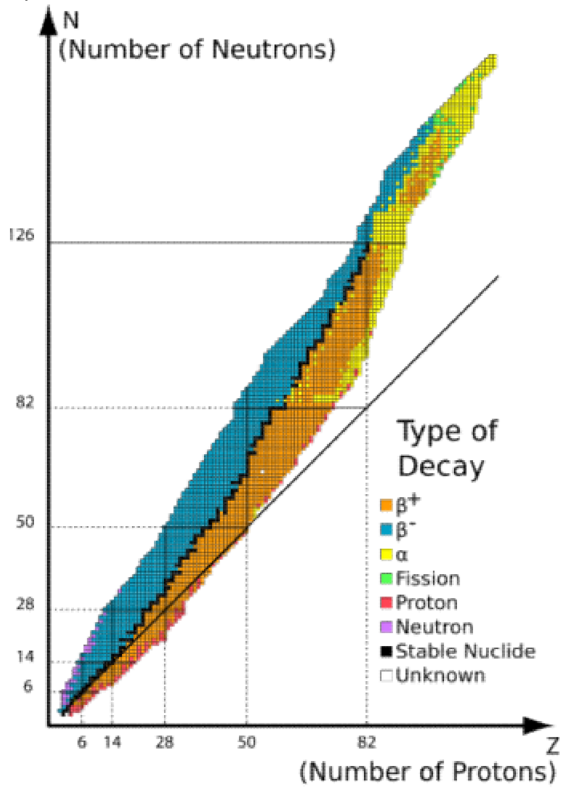
    - Normal cells will also be damaged but cancer cells are more affected
    - Gamma radiation pointed towards the cancer cells are emitted from many different angles → minimise the radiation exposure of other cells
- Sterilising medical equipment
    - Gamma radiation as it is the most penetrating
    - It can irradiate all sides of the instruments
    - It can sterilise the instruments without removing the packaging
- $^{99}\mathrm{Tc}^{\mathrm{m}}$(Technetium-99m) formation
    - The technetium is formed in an excited nuclear state
        - It will emit a gamma photon in order to reach the ground state
    - Technetium in metastable state
        - Metastable state = an excited state of the nuclei of an isotope that lasts long enough after alpha or beta emission for the isotope to be separated from the parent isotope
- Why Technetium-99m is used in medical diagnosis
    - Only emits gamma rays
        - Doesn't cause much ionisation so little damage caused
        - Easily detected outside the body as it is very penetrating
    - 6-hours half life
        - Short enough to not remain active in the body after use
        - Long enough to remain active during diagnosis
    - Its toxicity can be tolerated by the body
    - Easily prepared on site
- Safety issues
    - If radioactive particles enters the body, the radiation can cause mutations in one's DNA, thus causing cancer
        - E.g. radioactive gas such as radon can be inhaled and emit radiation inside lungs
    - Ionisation of atoms via gamma radiation only removes outer electrons but not the nucleus hence the ions produced are not radioactive
- Safety procedures
    - Using tongs / tweezers / handling tool
    - Remove source from lab / room when not in use / after experiment and store in a lead container
    - Stand behind a lead absorber / screen
    - Never point the source towards others or look directly into the source
    - Read local rules
    - Stay as far away from the radioactive source as possible
- Background radiation
    - The radiation that is present at all times
    - Sources of background radiation
        - Cosmic rays
        - Nuclear waste
        - Radon gas
        - Rocks
        - The Sun
    - They need to subtracted when doing calculations, giving **corrected count rate**

3.8.1.3 Radioactive decay

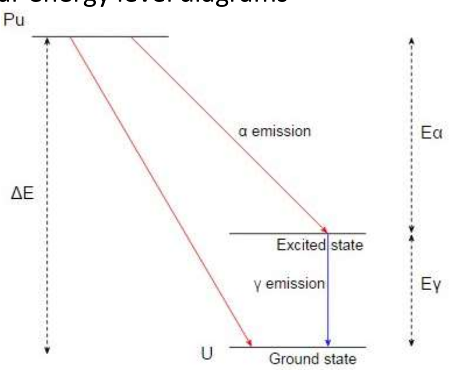
- Properties of radioactive decay
    - Random
    - Spontaneous
    - One particular **isotope** has a constant rate of decay
- Decay constant / λ
    - The probability of an individual nucleus decaying per second
- Activity
    - The number of nuclei of the isotope that disintegrate per second
    - $A = \lambda N$

- Unit = Becquerels (Bq) = decays per second
- Half-life / $T_{1/2}$
  - The average time it takes for the number of unstable nuclei of an isotope to halve
  - $T_{1/2} \times \lambda = \ln 2$
- Number of nuclei after a certain time
  - $\frac{\Delta N}{\Delta t} = -\lambda N = -A$
  - $N = N_0 e^{-\lambda t}$
  - In linear form: $\ln N = -\lambda \times t + \ln N_0$ (gradient = $-\lambda$)
- Activity after a certain time
  - $A = \lambda N_0 e^{-\lambda t} = A_0 e^{-\lambda t}$
- Radioactive dating
  - Nuclei with a long half-life e.g. C-14 can be used to date organic objects
  - Age determined by measuring the current amount in the dead body and comparing it to the initial amount (percentage of C-14 is approximately equal in all living things)
- Storage of radioactive waste with extremely long half-life
  - Stored suitably e.g. in still casks underground
  - Prevent these nuclei from damaging the environment and the people that may be living around them hundred of years into the future

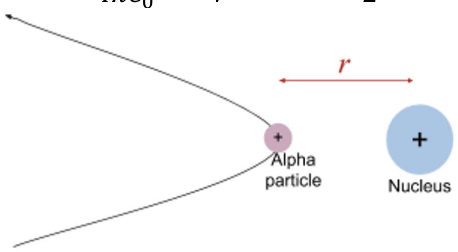
3.8.1.4 Nuclear instability

- N-Z graph
  - 

- Parts of the graph
  - Line of stability
    - Light isotopes ($0 \leq Z \leq 20$)
      - The stable nuclei follow the straight line $N = Z$
    - $Z > 20$
      - Stable nuclei have more neutrons than protons, neutron / proton ratio increases
      - The extra neutrons help to bind the nucleons together without inducing repulsive electrostatic forces as more protons would do
  - Alpha emitters
    - Occurs below the graph when $Z > 60$ i.e. heavy atoms / too many nucleons
    - The SNF between the nucleons is unable to overcome the electrostatic force of repulsion between the protons

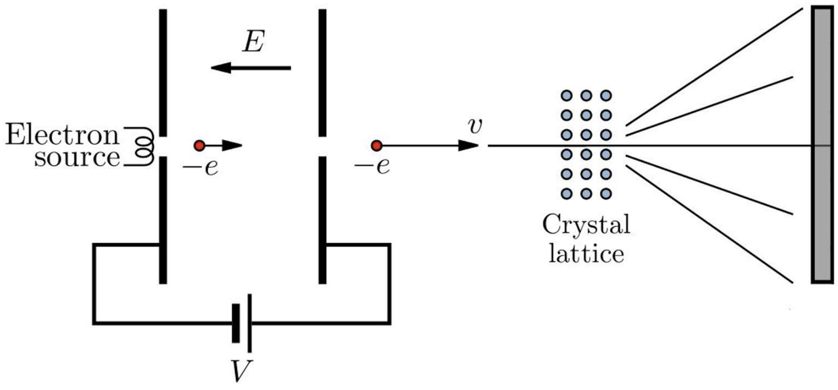
- $^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$
- Beta minus emitters
  - Occur above the graph when the isotopes are neutron rich
  - A neutron turns into a proton and the isotope stabilizes
  - $^{A}_{Z}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}\beta + \bar{v}_e$
- Beta plus emitters
  - Occur below the graph but above $N = Z$ when they are proton rich
  - A proton turns into a neutron and the isotope stabilizes
  - $^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + {}_{+1}^{0}\beta + \bar{v}_e$
  - Electron capture also happens in this region
- Electron capture
  - Occurs when the nucleus is proton rich
  - The proton absorbs an electron from the inner orbit of the atom and becomes a neutron, releasing v_e
  - The nucleus is thus excited
  - When the nucleus de-excites, a gamma photon is released
  - $^{A}_{Z}X \rightarrow {}_{Z-1}^{A}Y + {}_{-1}^{0}e + v_e$
- Nuclear energy level
  - Excited state
    - An atom which is not in its ground state (= the lowest energy state)
    - Usually short-lived and the atom de-excites to the ground state by emitting one or more γ photons
  - Ground state
    - The lowest energy state of an atom
- Nuclear energy level diagrams
  - 

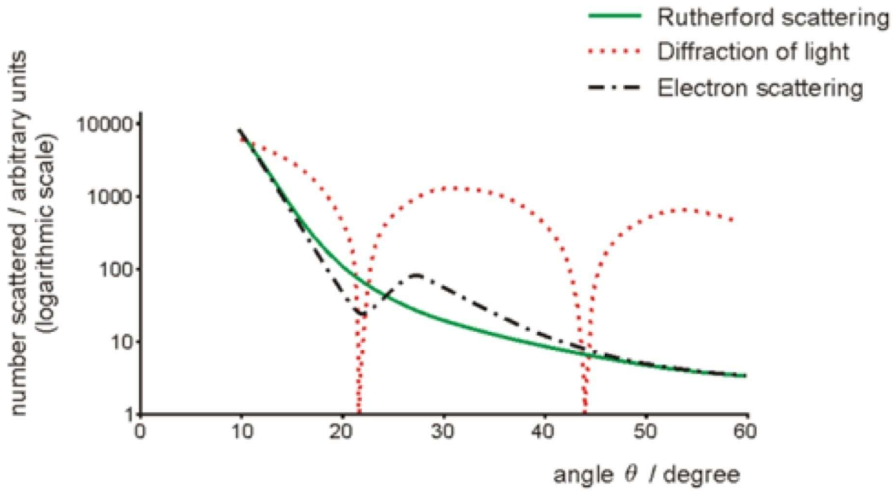
3.8.1.5 Nuclear radius

- Determination of nuclear radius by closest approach
  - Distance of closest approach = the point at which the particle stops and has no KE (all to electric PE)
  - $E_{elec} = \frac{1}{4\pi\varepsilon_0} \times \frac{Q_1 Q_2}{r} = E_k = \frac{1}{2}mv^2$
  - 

- Determining atomic radius with electron diffraction
  - The electrons are accelerated to very high speeds so that their De Broglie wavelength is around 10^{-15} m (about the same size as a nucleus)
  - Electrons are directed a very thin film of material and are **diffracted by the nuclei**
  - Diffraction pattern formed on screen = a set of concentric circles with a central bright spot, gets dimmer moving away from centre
  - Plot a graph of intensity against diffraction angle using a detector

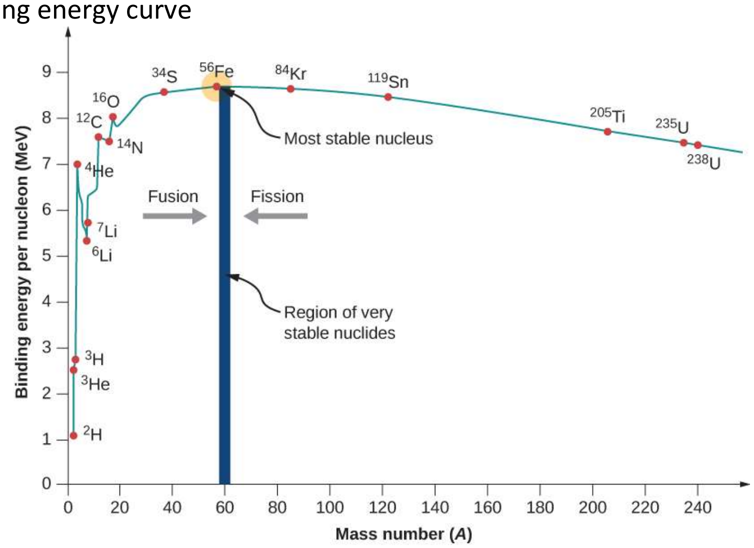
61λ

- Estimate the nucleus radius using $\sin\theta = \frac{0.61\lambda}{R}$ (θ = diffraction angle of the first minimum, λ = De Broglie wavelength of the electrons $\approx 1 \times 10^{-15}$ m)
- 

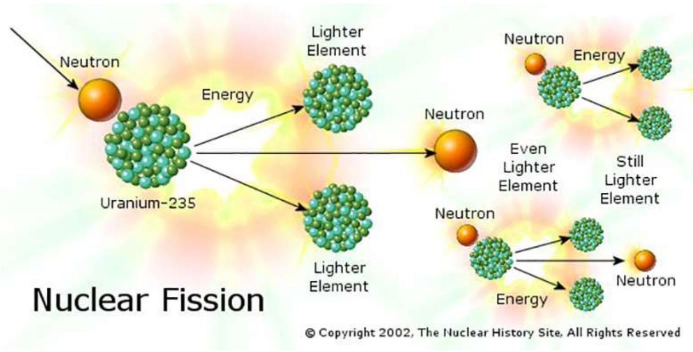
- Observation patterns
  - As the angle of the detector θ from the zero order beam is increased there is alternating decrease and increase in intensity
  - The resultant curve is the sum of two components
    - Rutherford scattering
    - Electron diffraction
- 

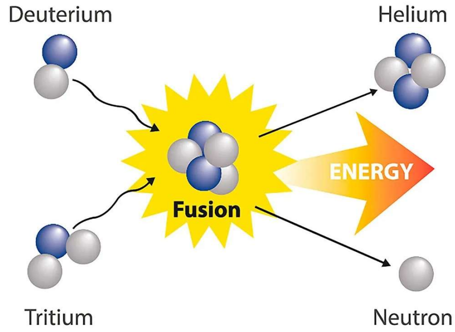
- Why are alpha particles not used for diffraction
  - Strong forces complicate the process
  - Scattering caused by distribution of protons not whole nucleon distribution
  - Alpha particles are massive causing recoil of nucleus which complicates results
- Nuclear radius
  - $R = r_0 A^{\frac{1}{3}} = r_0 \times (\text{mass number})^{\frac{1}{3}}$
  - $r_0 = 1.05 \text{ fm} = 1.05 \times 10^{-15} \text{ m}$
  - $V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi r_0^3 A$
- Evidence of nuclear radius formula from experimental data
  - $\ln R$ against $\ln A$: gradient = $\frac{1}{3}$, y-intercept = r_0
  - R against $A^{\frac{1}{3}}$: gradient = r_0, y-intercept = $(0, 0)$
- Nuclear density
  - Nuclear density is **a constant**
  - $\text{Nuclear density} = \frac{Au}{\frac{4}{3}\pi r_0^3 A} \approx 3.4 \times 10^{17} \text{ kg m}^{-3}$
    - 1 u = 1 atomic mass unit = 1.661×10^{-27} kg
  - Assumptions
    - The nucleus is spherical
    - All of nuclei have the same density
    - Total mass = mass of constituent nucleons

3.8.1.6 Mass and energy

- Mass and energy interchanging
  - $E = mc^2$
  - When energy is released mass also decreases / when energy is gained mass also increases
  - Applies to **all energy changes**
- Mass defect / mass difference
  - The difference between the mass of the nucleus and the sum of the masses of its nucleons
  - **The mass of a nucleus is always smaller than the mass of its constituents**
  - Lost mass is converted into energy and released when the nucleons fuse to form a nucleus
- Binding energy
  - The amount of energy required to separate a nucleus into individual nucleons / the energy released when a nucleus is formed from its constituents
  - $E = \Delta m \times c^2$
- Atomic mass units (u)
  - $1\ u = \frac{1}{12}$ of the mass of a carbon-12 atom = 1.661×10^{-27} kg
  - $u = \frac{1}{12} \times \frac{12}{N_A} = \frac{1}{N_A}$ in grams
  - Change in 1 u of mass = 931.5 MeV of energy is released
- Binding energy curve
  - 

  - Average binding energy per nucleon $= \frac{\text{binding energy}}{\text{number of nucleons}}$
  - Peak at A = 56 (8.7 MeV) → **iron** has the highest binding energy per nucleon and is the most stable
  - **Binding energy per nucleon will increase** after fission or fusion
    - Nuclei smaller than iron can undergo nuclear fusion
    - Elements larger than iron can undergo nuclear fission
  - Higher binding energy means that more energy is needed to separate the nucleus into separate protons and neutrons and hence the nucleus is more stable
- Nuclear fission
  - The splitting of a large atomic nucleus into smaller nuclei (daughter nuclei)
  - Occurs in very large nuclei which are unstable e.g. uranium completely randomly
  - Fission fragments tend to have a higher N/Z ratio than stable nuclei
    - Become neutron or beta minus emitters

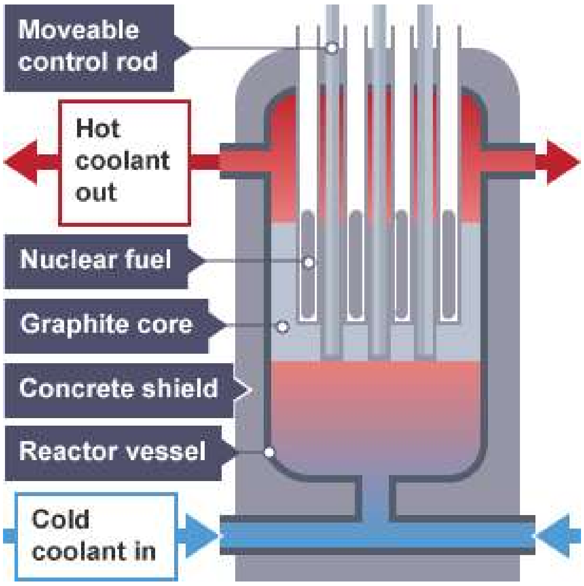
- 

- Nuclear fusion
    - Two smaller nuclei join together to form one larger nucleus
    - Only occurs in small nuclei
        - Good sources = deuterium (2-hydrogen) and tritium (3-hydrogen)
    - A lot more energy is released during fusion because the larger nucleus has a much higher binding energy per nucleon
    - Fusion can only occur at extremely high temperatures since a massive amount of energy is needed to overcome the electrostatic force of repulsion between nuclei
    - 

- Advantages of fusion vs fision
    - Greater power output per kg
    - Raw materials are cheap and plentiful
    - No radioactive elements produced directly
    - The reactor can become radioactive but the materials have short half-lives
- Problems with fusion reactors
    - Need to get 2 nuclei close enough
    - Sun has high temperature and pressure
    - On Earth the same pressure is impossible so very hot temperatures of about 100 million K is needed (Sun's core is 15 million K)
    - Need to contain the hot gas with very strong magnetic fields
    - It takes more energy to create the temperature and pressure than the energy released
- Benefit of nuclear physics knowledge to society
    - Knowledge of the physics of nuclear energy allows society to use science to inform decision making
        - e.g. risks of nuclear power station

3.8.1.7 Induced fission

- Thermal neutrons
    - Slow moving neutrons with low kinetic energy
    - They are in thermal equilibrium with the moderator / other material
    - Can be absorbed by fuel nuclei to cause fission
- Inducing nuclear fission
    - Fission can be induced by firing thermal neutrons into the nucleus
    - The nucleus absorbs the neutron and becomes extremely unstable
    - Split into nuclei fragments + releasing several neutron**s**
    - Neutrons released can be absorbed by other nuclei and induce more fission processes
    - A chain reaction created where each fission goes on to cause at least one more fission
        - **Uranium-235** captures a thermal neutron and splits into 2 smaller nuclei **releasing more**

neutrons
    - At least one of these neutrons go on to cause further **splitting / fissioning** of uranium-235
- Why is energy released in induced fission
    - Fragments created after fission repel each other
    - Repulsion overcomes strong force
    - Fragment nuclei and neutrons gain KE
    - Fragments are more strongly bound than the parent nucleus so energy is released when they bind together
- Nuclear reactor structure
    - 

- Shielding
    - Often thick concrete
    - Neutrons are absorbed by nuclei in the shielding
    - The nuclei of the shielding become unstable isotopes and can decay by fission (becomes radioactive)
- Fuel rods
    - Mixture of U-235 and U-238
        - U-235 absorbs neutrons → become U-236 → fission → more neutrons and energy released → chain reaction
        - U-238 absorbs neutrons → controls rate of reaction
    - Enriched uranium (higher ratio of U-235 to U-238)
        - Mass of U-235 must be greater than the critical mass
        - Critical mass = the minimum mass of fuel required to maintain a steady chain reaction
- Control rods
    - The nuclei in control rods absorb any neutron that collides with it, thus controlling the rate of fission
    - Insert rods further into the reactor → more neutrons absorbed → lower rate of fission reactions → lower power output
    - During normal operation they are adjusted to leave **one neutron per fission and maintain a constant rate of reaction**
- Control rods material choice
    - Made with non-fissionable isotopes that can absorb neutrons
    - Common material used = boron / silver / indium / cadmium
- Moderator
    - Neutrons undergo elastic collisions with moderator nuclei and bounce off with less KE
    - Slows down / reduces the kinetic energy of neutrons so they become **thermal neutrons**
    - Neutrons can now be absorbed by the uranium / fuel and cause fission
- Material for moderator
    - Light nuclei
        - More KE can be transferred to the moderator nuclei when the mass is similar to neutron
        - Lower nucleon number reduces the number of collisions for a neutron to slow down

enough to be absorbed by fuel nuclei
    - Moderator nuclei should not be fissionable and should not absorb neutrons
        - Can still become gamma emitters after being excited by collision as energy gaps are large
    - Common material = graphite / water / beryllium / heavy water
- Coolant
    - Remove the heat released by the reactions
    - Delivers the heat to the boiler / turbine via a heat exchanger
    - The boiler heats up water, and the steam will be used to power electricity-generating turbines
- Coolant material choice
    - It should not absorb neutrons / have small neutron absorption cross-section
    - Stability under conditions of high temperature and high levels of radiation
    - Non-corrosive
    - Unreactive
    - High boiling point
    - Low ability to flow
    - High specific heat capacity
    - Water is normally used as moderator as it has high specific heat capacity
- Advantages and disadvantages of nuclear power
    - Advantages
        - Small amount of fossil fuel used so there is little greenhouse gas emissions & cleaner air due to reduced GHG emission
        - Small amount of fuel is consumed to get a large amount of energy
        - Nuclear power can be produced continuously (whereas renewables often depends on wind / sunlight conditions)
        - Some nuclear power stations can adjust their output quickly
        - Benefits of producing medical isotopes
    - Disadvantages
        - Hazardous waste from radioactive fission fragments or used fuel uranium rods
- Types of thermal reactor
    - PWR (pressurised water reactor)
    - AGR (advanced gas reactor)

3.8.1.8 Safety aspects

- Reducing the exposure of workers to radiation
    - Remote handling of fuel rods
        - They are much more radioactive after removal from the reactor
        - α emitter → strong β and γ emitter due to neutron-rich fission products
    - Thick concrete shielding
        - Vessel is thick steal designed to withstand great pressure and temperature + absorbs β and some γ radiation
        - Core is in a very thick concrete building which absorb neutrons and γ radiation
    - Emergency shut-down
        - When leakage / accident occurs, control rods are fully lowered to absorb all neutrons
        - The reaction is stopped as soon as possible
- Radioactive waste from reactors
    - Fission fragments from the fission of the uranium-235 or from spent fuel rods
- Handing of high-level waste (used fuel rods)
    - Remote handling (see above)
    - Waste initially placed in cooling ponds / water for a number of years
    - Plutonium / uranium is separated to be recycled
    - High level waste is vitrified / made solid into pyrex glass and then placed in lead / concrete containers to be stored **deep** underground
- Challenges with high-level waste handling
    - The waste is initially very hot
        - Must be placed in cooling ponds to remove the heat

- The waste is initially very radioactive
    - Needs to be screened in water / cooling ponds to absorb the radiation + remotely handled
- The waste may leak in liquid form
    - Vitrified and barrel in steel
- The waste remains radioactive for hundreds / thousands of year
    - Storage needs to be stable in a container hence vitrified
    - Store in geologically stable areas deep underground
- Transport waste presents a potential danger to the public
    - Waste is transported enclosed in crash resistant and strong casings
    - Alternatively waste can be processed onsite or nearby

- Handling of intermediate-level wastes
    - Sealed in drums and encased in concrete
    - Stored in special concrete buildings
- Handling of low-level wastes
    - Laboratory equipment and protective clothing needed to remove
    - Sealed in metal drums and buried in trenches
- Benefits of nuclear power
    - Little greenhouse gas produced
    - Less fuel needed to produce the same amount of energy
    - Some power stations can adjust output quickly
    - Medical isotopes is produced
- Risks
    - Hazardous waste produced
    - Nuclear meltdown is catastrophic to the environment and the public