AQA Physics A-level

Topic 12: Turning Points

Key Points

Cathode Rays

In the 1870s William Crookes carried out an experiment that discovered the existence of cathode rays. The **observations** from this experiment were:

- If gas of a **low enough pressure** is sealed in a glass tube, it will **conduct** electricity
- The gas will **glow** near both the **positive anode** as well as the **negative cathode**
- When a **magnet** is held near the tube, the glowing regions become **distorted**
- When a **'paddle wheel'** was added to the tube, it was forced to **rotate** by the radiation from the cathode

The **conclusions** drawn from these observations were:

- Radiation is emitted from the cathode, and this is known as a **cathode ray**
- The cathode ray is **charged** since it is deflected by a magnet

Further experiments by **JJ Thomson** showed that the particles in the cathode rays were the same regardless of what gas was being used, and that they were **negatively charged**. These particles became known as **electrons**.

Light Emissions from a Discharge Tube

In the experiment discovering the existence of cathode rays, a glow of light was observed at both the positive and negative sides of the discharge tube. This **emission of light** is explained as follows:

- A **high voltage** is applied across the gas - this produces a **strong electric field** which pulls electrons from the gas atoms, causing them to become **ionised**
- These positive ions are attracted to the cathode, where they cause electrons to be **emitted** from the surface
- The electrons emitted from the cathode are **accelerated** towards the anode, and ionise more gas atoms on the way

The **negative glow** is produced when positive ions **rejoin** with electrons near the cathode and release **photons** in the process.

The **positive glow** is produced when cathode rays move towards the anode and cause **excitation** of gas atoms - when these atoms **de-excite**, photons are emitted and produce the 'positive glow'

Both glows produced are in the **visible** and **ultraviolet** range of the EM spectrum.

Thermionic Emission

An easier method of producing an electron beam is through **thermionic emission**. This is when a metal is **heated**, resulting in **free electrons** inside the metal gaining **sufficient kinetic energy** to leave the metal's surface. The most common method of achieving this is with a **wire filament**:

- A current is passed through the filament
- The filament heats up, and free electrons gain kinetic energy
- Electrons that gain sufficient kinetic energy are released from the surface

To **accelerate** the electrons that are released, and to produce a beam, an **anode** is placed opposite the filament. There is a **vacuum** between the filament and this anode, which allows the electrons to be accelerated across the gap. There is a **small hole** in the anode that the electrons then pass through.

If you know the accelerating voltage, it is possible to **calculate** the **speed** of the electrons as they pass through the hole. All the **kinetic energy** that electrons have, comes from the **work done** by the potential difference, and so:

$$eV = \frac{1}{2} m v^2$$

Specific Charge of Electrons

Specific charge is the **ratio of charge to mass**. As an equation it is:

$$\textit{Specific Charge} = \frac{Q}{m}$$

Prior to the discovery of the electron, the highest measure specific charge was that of a **hydrogen ion**, however when Thomson discovered the electron, the **electron** became the **largest** known specific charge.

You should be aware of **three** main methods for **measuring** an electron's specific charge:

1. Deflection in a magnetic field
2. Balancing fields
3. Deflection in an electric field

Deflection in a Magnetic Field

In the magnetic field deflection method for measuring specific charge, an **electron gun** fires electrons into a perpendicular **magnetic field**. This causes the electrons to travel in a **circular motion**. The radius of the curvature is measured and then the specific charge can be calculated as follows:

1. The **magnetic force** on the electrons is the **centripetal force** causing the circular motion and so:

$$Bev = \frac{mv^2}{r} \qquad r = \frac{mv}{Be}$$

2. The **work done** by the anode potential (V_a) is equal to the **kinetic energy** of the electrons:

$$eV_a = ½\, m\, v^2$$

3. Combining the above two equations, and rearranging for e/m gives:

$$\frac{e}{m} = \frac{2V_a}{B^2r^2}$$

Balancing Fields

The balancing fields method for measuring the specific charge of an electron involves passing a beam of electrons between two charged plates in the presence of a perpendicular magnetic field. The electric and magnetic fields are such that the beam of electrons passes through undeflected. This means that the two fields are equal to each other.

When the fields are balanced, the electric force equals the magnetic force, allowing the speed of the electrons to be calculated:

$$eE = Bev \quad \textit{meaning...} \quad v = \frac{E}{B} \quad \textit{where...} \quad E = \frac{\textit{pd between plates}}{\textit{plate separation}}$$

The speed can then be substituted into the equation derived on the previous page and rearranged to find the specific charge:

$$r = \frac{mv}{Be}$$

Deflection in an Electric Field

The deflection in an electric field method for measuring electron specific charge involves firing electrons of a known speed into a **uniform electric field** of known length. The **vertical deflection** of the beam when it reaches the end of the electric field is measured and the **specific charge** can be calculated as follows:

1. The **time** taken for an electron is given by:

$$t = \frac{\text{Plate Length}}{\text{Electron Speed}}$$

2. The **acceleration** of the electron towards the positive plate is calculated using:

$$y = \tfrac{1}{2} a t^2$$

Where y is the vertical deflection of the beam within the field.

3. By applying **Newton's second law**, where the force is the electric force produced by the field, e/m can be calculated:

$$F = \frac{eV}{d} \qquad a = \frac{eV}{md} \qquad \frac{e}{m} = \frac{ad}{V}$$

Millikan’s Oil Drop Experiment

Millikan’s oil drop experiment is an experiment used to determine the **charge of an electron**. It involves two main steps:

1. Calculating the **radius** of a charge oil drop by taking measurements as it falls at **terminal speed**
2. Holding the drop **stationary** by balancing its **weight** and an **electric field**

Oil drops were **ionised** with the same charge using a **atomiser**. This created a fine mist of charged oil droplets. These drops then passed through a hole in the top plate of a **uniform electric field**.The drops were observed through a **microscope** that had a scale on which allowed for calculations of quantities such as distance and speed to be carried out.

Millikan's Oil Drop Experiment

When an oil drop falls freely, with no electric field present, there are two forces acting on it:

1. An **upwards drag force** equal to:

$$Drag = 6\pi\eta r v$$

2. A **downwards weight** equal to:

$$W = mg \qquad m = v\rho \qquad v = 4/3\pi r^3 \qquad W = 4/3\ \pi r^3 \rho\ g$$

When it is travelling at **terminal speed**, the drag force must equal the weight. This allows the **radius of the oil drop** to be calculated:

$$6\pi\eta r v = 4/3\ \pi r^3 \rho\ g \qquad r^2 = \frac{9\eta v}{2\rho g}$$

Millikan's Oil Drop Experiment

To hold the oil drop **stationary**, the electric field is turned on. When the drop is stationary, the upwards force from the **electric field**, equals the downwards acting **weight** of the oil drop:

$$W = \frac{QV}{d}$$

This can then be combined with the equations for weight and radius and rearranged to calculate the **charge** of the drop.

The **conclusions** that Millikan drew from his calculations were:

- All drops had a charge that was a multiple of 'e'
- This suggested that charge was **quantised**
- The smallest possible charge is 'e'
- 'e' is the charge of a single electron

Newton’s Corpuscular Theory of Light

Newton believed that light consisted of small packets that he called **corpuscles**:

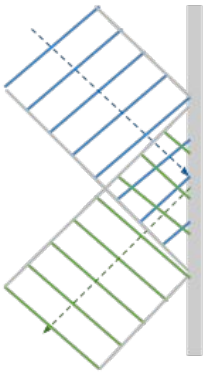
- **Reflection** was thought to be caused by the corpuscles reaching the surface and being acted on by a repulsive force that changed their direction
- **Refraction** was thought to be caused by a **perpendicular** force acting on the corpuscles as they enter a new medium, causing a perpendicular acceleration - the **parallel** component of the corpuscles’ motion remains unchanged
- **Diffraction** could not be explained by this theory
- The theory predicted that light should travel **faster** in denser mediums

Newton’s corpuscular theory of light was favoured over other theories of the time due to Newton’s strong **reputation**. The theory was later proved to be **wrong** by **Fizeau’s** experiments measuring the speed of light, which concluded that light in fact travels **slower** in denser mediums.

Huygen's Wave Theory of Light

Huygen's Wave Theory of Light predicted that light consisted of **wavelets** which each acted as **point sources**.

- Each point on a **wave front** acts as a secondary wavelet from which further waves spread out from
- **Reflection** is explained by the fact that different parts of the wave front will reach the surface at a different time, causing the wavelets to spread from the surface at the point they reach it at to form the reflected wavefront
- **Refraction** was explained by applying the theory that light travels **slower** in a **more dense** medium - this was a key **difference** with Newton's corpuscular theory



Measuring the Speed of Light

Before **Fizeau's experiment**, an accurate measurement of the speed of light wasn't known. Fizeau's experiment consisted of a light source 8.6km from a mirror, with a toothed wheel in between. The process was as followed:

1. A **beam of light** was shone at the **mirror**, and the toothed wheel was rotated at high speeds
2. Initially, at **lower speeds** the light passed through a gap in the wheel, reflected off the mirror and was **observed** to return through the same gap
3. As the speed of the wheel **increased** however, it reached a frequency of rotation whereby the light passed through a gap, was reflected but was then **blocked** by the adjacent tooth, preventing it being observed

If the **frequency** of the wheel's rotation and the number of teeth and gaps it has is known:

A tooth replaces a gap every $\frac{1}{2n}$ *of a rotation, and so every* $\frac{1}{2nf}$ *seconds.*

This means that the speed of light is given by: $\frac{2d}{\frac{1}{2nf}} = 4dnf$

Where 'n' is the number of teeth or gaps, 'f' is the frequency of rotation and 'd' is the distance from the light and the mirror.

Maxwell's Theory of Electromagnetic Waves

Maxwell predicted that electromagnetic waves consisted of perpendicular oscillating **electric** and **magnetic** fields. He also derived an equation for their speed:

$$C = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$$

- *μ_0 is a constant linking the magnetic flux density of a field to the current that produces it*
- *ε_0 is a constant linking the strength of an electric field to the charge that produces it*

He demonstrated that:

- Light travels the **same speed** in a vacuum as it does in free space
- **Light** is part of the electromagnetic spectrum
- **Infrared** and **UV** radiations are also part of the spectrum

Maxwell's theories were proven correct by later discoveries of **X-ray** and **radio waves**, which demonstrates how theory that is backed up by subsequent experiments becomes accepted by the **scientific community**.

Hertz

Hertz discovered that **radio waves** are generated when **high voltage** sparks cross a small **air gap**. These waves can be detected by:

1. Using a **wire loop** with a small gap
2. A set-up, of two parallel rods in a concave reflector, known as a **dipole**

His experiments showed that the radio waves:

- Could produce stronger sparks at the detector by placing a **concave metal sheet** behind the transmitter, showing they can be **reflected**
- Could form a **stationary wave** by reflecting them from a flat metal sheet
- Are **polarised**, since if you rotate the detector out of line with the transmitter, the sparks will be reduced
- Are **not** stopped by **insulators**

Frames of Reference

The **two postulates** for **Special Relativity** are:

1. The **laws of physics** have the **same form** in all **inertial frames**
2. The **speed of light** is **invariant**

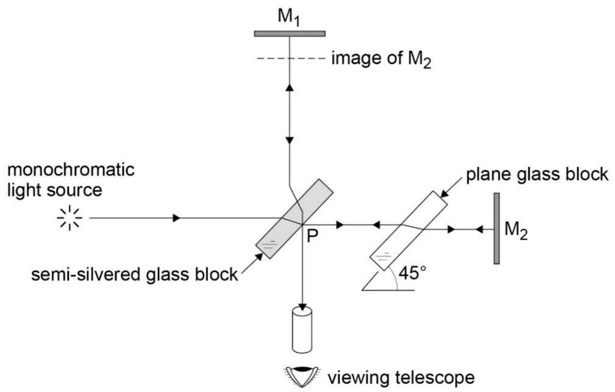
An **inertial frame of reference**, is one that is not accelerating. An alternative way of expressing this, is that there is no net force acting.

The postulate that the speed of light is **invariant** means that the speed is the **same** for **all** observers regardless of any motion of the observer or relative motion of the light source.

The Michelson-Morley Experiment

The Michelson-Morley experiment aimed to measure the **absolute speed** of the Earth through the **ether**. The prediction was that if light travelled through an ether, it should travel at a **different speed** in the direction of the Earth's motion compared to opposite it.

- Light was shone at a **semi-silvered** glass block that split the light into two perpendicular beams
- Each beam was reflected off a mirror of an **equal distance** away
- The reflected beams join back together, and form an **interference pattern** which is observed by a viewing telescope



Note that there is a **plane glass block** between P and M2 so that both rays travel the **same distance** and pass through a glass block the same number of times.

The Michelson-Morley Experiment

The **expected** results from the **Michelson-Morley** experiment were:

- The **time taken** for the ray to travel in the Earth's direction of motion and back would be greater than the time taken for the ray travelling perpendicular to the Earth's motion
- Rotating the apparatus through 90 degrees would cause the time difference to switch
- As the apparatus is rotated, there would be a shift in the **fringe pattern**

In **reality** the experiment showed that:

- There was **no noticeable shift** in the fringe pattern
- This was despite the equipment being able to detect shifts as small as **0.05** of a fringe

The **conclusions** that were drawn were:

- There is **no absolute motion**
- The **ether doesn't exist**

An alternative conclusion that some scientists made, was that the Earth dragged the ether with it, but this was later rejected.

Time Dilation

Time dilation is a consequence of the invariance of the speed of light. You can remember the effect of time dilation using the phrase:

"A moving clock always runs slow"

$$t = t_0 \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$$

Length Contraction

Length contraction is another consequence of special relativity, which can be remembered with the phrase:

"A moving rod looks shorter"

$$l = l_0 \left(1 - \frac{v^2}{c^2}\right)^{\frac{1}{2}}$$

Relativistic Energy

Einstein also carried out calculations considering the **conservation of momentum** in different inertial frames of reference, and formulated the following expression linking mass and velocity:

$$m = \frac{m_0}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$$

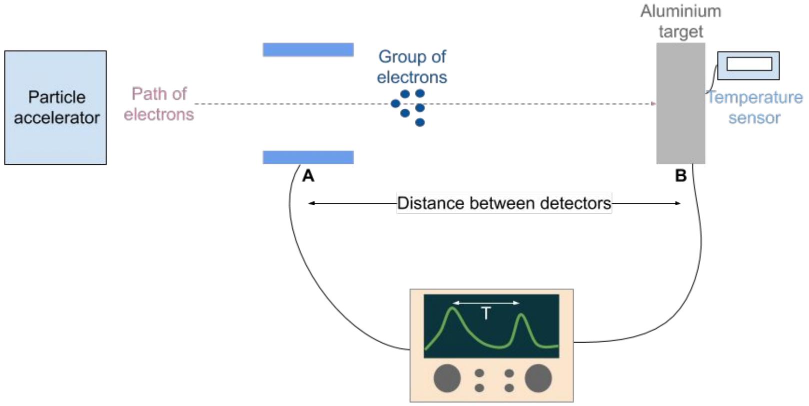
The above equation shows that:

- **Mass increases** with an increase in speed
- The mass becomes **infinitesimally** large as it reaches the **speed of light**

Bertozzi's Experiment

Bertozzi's experiment aimed to measure how an electron's **kinetic energy** varied with **velocity**.

- Bunches of electrons were fired after being accelerated over a differing potentials
- The **speed** of the electrons was calculated by timing the time they took to travel the known distance between detectors
- At the far end, the electrons collided into a metal plate that absorbed their **kinetic energy** as heat energy, allowing the energy they had to be calculated using the **temperature rise** of the plate:



$$E_k = mc\Delta\theta/n$$

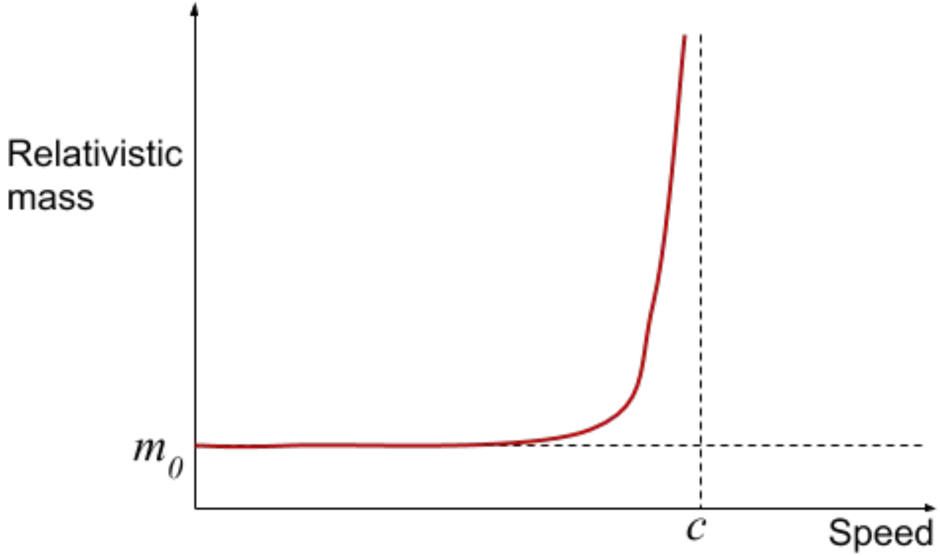
Where 'm' is the mass of the plate and 'n' is the number of electrons.

Bertozzi's Experiment

Bertozzi's experiment showed that the variation of kinetic energy with velocity only agreed with **classical predictions** for very low speeds.

The data from the experiment showed how at high speeds, relativistic effects must be taken into account. In reality, the variation of kinetic energy with velocity uses the below relativistic energy formula:

$$\frac{m_0c^2}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}} - m_0c^2$$



The Ultraviolet Catastrophe

A **black body** is a body that emits all the possible wavelengths of radiation for the temperature that it's at. The **ultraviolet catastrophe** is a disagreement between the **classical prediction** and the **observed data**, of how the **energy intensity** being emitted should vary for **different wavelengths**:

- **Classical theory** predicted that most of the energy would be emitted in the UV range, and would be infinite at the very smallest wavelengths
- **Observed data** show there is a peak at a longer wavelength than expected, and that it appears at a shorter wavelength as temperature increases

Planck's idea of energy existing in **quanta** helped to solve this disagreement:

- Radiation is emitted in 'packets' which are linked to a single frequency
- $E=hf$ meaning high frequency radiation is emitted in **larger** 'packets'

Photoelectric Emission

When Hertz was carrying out experiments investigating radio waves, he discovered that by shining UV light on the spark gap, the sparks produced were stronger. He observed that:

- No photoelectric emission occurs if the light is below the **threshold frequency**
- The emission is **instantaneous** if above the threshold frequency
- The photoelectrons emitted have a **range of kinetic energies** up to a maximum
- The number emitted is proportional to the **intensity** of the light

This led to the explanation of the photoelectric effect in terms of the **particle-like nature** of light:

- Each photon of light has 'hf' energy, and each photon transfers this energy to a **single** electron
- If the energy transferred is great enough for the electron to overcome the metal's **work function** and pass out to the surface of the metal, it will be released
- Any excess energy will be in the form of **kinetic energy**:

$$E_{kmax} = hf - \phi$$

Electron Diffraction

De Broglie suggested that matter particles have a wave-like nature as well as their particle-like nature. He formed the equation:

$$mv \times \lambda = h$$

Where 'h' is Planck's Constant

This theory was later proved to be correct, after experiments which showed the diffraction of electrons:

The electron diffraction interference pattern forms concentric rings

Transmission Electron Microscopes

The **transmission electron microscope** makes use of the idea that electrons will be able to produce a much higher resolving power than light waves. The process is as follows:

1. Electrons are produced by **thermionic emission** and accelerated over a **high voltage**
2. They pass through soft iron **magnetic lenses** that deflect the rays towards the central axis, or in the case of rays that are already travelling centrally downwards, leave them undeflected
3. The **condenser lens** spread the electrons into a **wide beam** that passes over the sample
4. The **objective lens** magnifies the image and the **projector lens** magnifies, focuses and projects it onto the screen

It is important that the electrons have the **same speed** since the magnetic force they experience depends on speed, and so different speeds will lead to different magnitudes of force and a **blurry** image.

Increasing the p.d will increase the speed, which will reduce the de Broglie wavelength, and result in a **higher resolution** image.

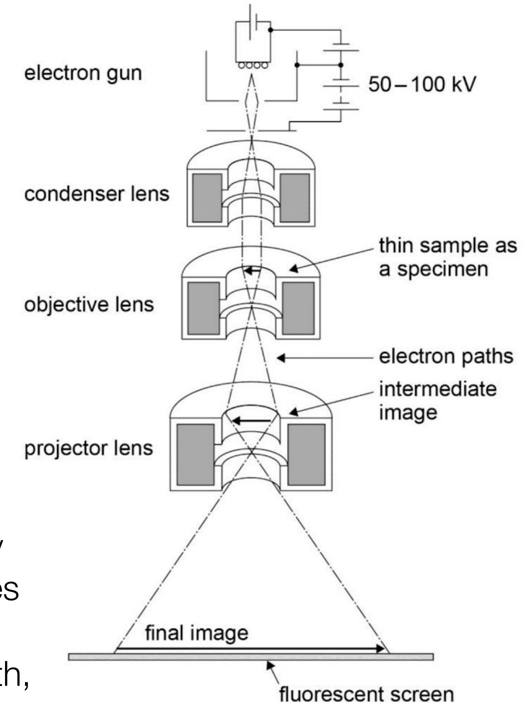


Image from the AQA Turning Points Teaching Guide

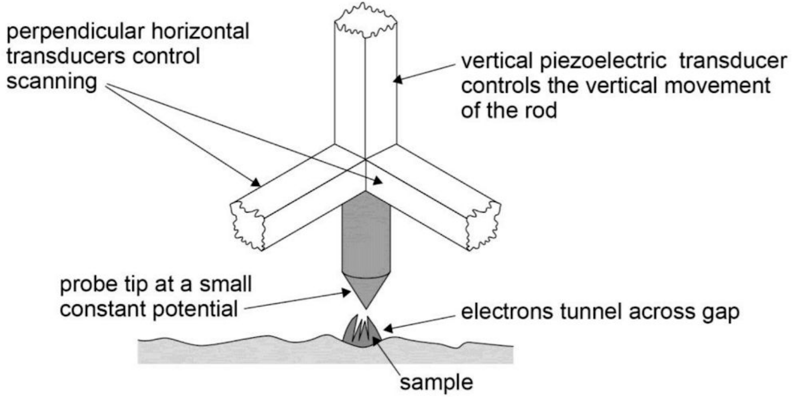
Scanning Tunneling Microscopes

Scanning Tunneling Microscopes scan and form images of a sample's surface. It consists of a probe that is controlled by piezoelectric transducers. This allows its motion to be controlled to the nearest **0.001nm**. The probe has a constant potential, and is held up to 1 nm from the sample's surface.

Quantum tunneling is the idea that a wave's amplitude isn't always reduced to zero if passing through a thin barrier. It is applied to matter waves, and explains why electrons can 'tunnel' across the small gap.

There are two modes that an STM can operate in:

1. **Constant Height Mode**: the height of the probe remains constant, and the current changes as the surface moves closer or further away from it, allowing an image to be built up
2. **Constant Current Mode**: the probe changes height as it passes over the surface so that the current is maintained constant. An image is built from these changes.



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