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11.1 The Discovery of the Electron

Turning Points in Physics

AQA A Level Revision Notes

A Level Physics AQA

12.1 The Discovery of the Electron

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12.1.1 Cathode Rays

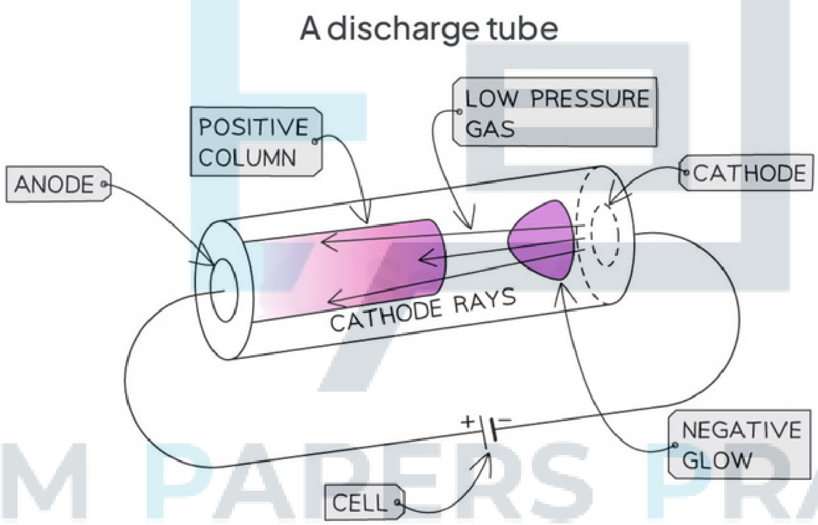
Cathode Rays

What is a Cathode?

- An electrode is a conductor through which electricity passes
- A cathode is a **negatively charged** electrode
- An anode is a **positively charged** electrode

Discharge Tubes

- In the 1800s, scientists made discharge tubes
  - These were glass chambers containing a low pressure gas, with an anode at one end and a cathode at the other, connected to a high voltage supply
- When a potential difference was applied between the anode and cathode, the gas **glowed**
  - It was hypothesised that this glow was caused by emissions from the cathode, called **cathode rays**



What are Cathode Rays?

- When a magnetic field was applied to the glass tube, it was found the path of the cathode rays was deflected
  - This showed they were made from **negatively charged particles**

How does the Discharge Tube Conduct?

- The electric field between the electrodes **ionises** the gas particles in the tube
- This separates atoms into positive ions and electrons
  - Negative electrons are attracted to the positive **anode**
  - Positive ions are attracted to the negative **cathode**
  - This can only happen because the pressure of the gas is low enough to allow the charged particles to travel
- Electrons are also **emitted** from the cathode and travel towards the anode

- Conduction is a result of these electrons and positive ions moving across the tube

Why does the Gas Glow?

- Electrons and positive ions are travelling in opposite directions in the tube
  - Due to the **low pressure**, they have space to gain a large amount of energy in their kinetic store
- When they collide, they recombine in an **excited** state
- The electrons in atoms de-excite to ground state, emitting visible photons (as well as other frequencies)

Worked Example

A discharge tube contains a low pressure gas. An anode is at one end and a cathode at the other with a large potential difference between the two. The gas conducts and also emits light.

(i) Explain how the gas conducts, referring to the charge-carrying particles in your answer.

(ii) Explain why the gas must be at low pressure to emit light.

Answer:

(i)

Step 1: Recall that, for the gas to conduct, we need charged particles

- The electric field ionises gas atoms, removing electrons and forming positive ions
- The cathode also emits electrons (at very high potential difference)

Step 2: Recall why the particles move across the discharge tube

- The electric field accelerates electrons and positive ions, which cause conduction

(ii)

Step 1: Light is emitted when electrons and ions recombine

- Positive ions and electrons collide at high speed and recombine, emitting photons when they de-excite

Step 2: Light is emitted when an atom is excited

- Accelerated electrons collide with gas atoms, exciting them
- The gas atoms emit visible photons when they de-excite

Step 3: Describe a low pressure gas in terms of the distribution of particles

- In a low pressure gas, the particles are widely spaced

Step 4: Recall why this allows atoms to become excited more easily

- There are fewer obstacles for accelerating charged particles, so they can collide with enough energy to produce excited atoms (which then go on to emit light)

12.1.2 Thermionic Emission

Thermionic Emission

How do you Create a Cathode Ray?

- We now know that cathode rays are **electrons**
- The first discharge tubes produced cathode rays from the cathode using a **strong electric field** to "pull" electrons across the tube
- Forming a cathode ray can be made easier by **heating** the cathode - this is called **thermionic emission**

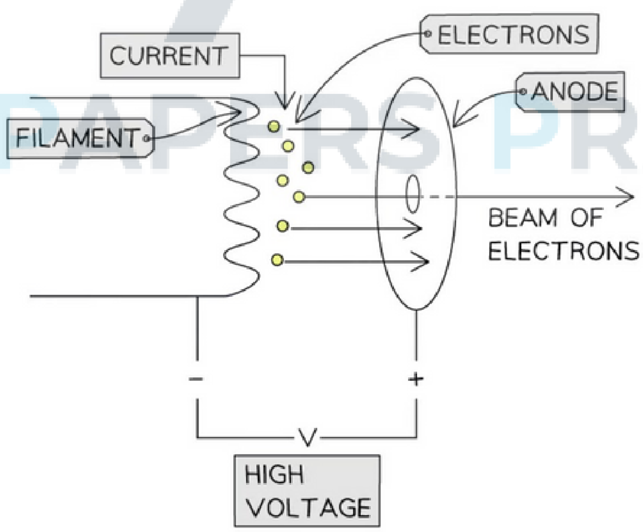
Thermionic Emission

- The electrons in the **heated** cathode (also called a **heated filament**) have more energy in their kinetic stores
    - This is enough to leave the surface of the metal and move towards the anode

Cathode Ray Tubes

- These are designed to "fire" the electrons emitted from the cathode towards a target - sometimes these are more dramatically called **electron guns**
- Electrons are accelerated towards the anode, but pass through a hole in it and continue towards their target

Cathode Ray Tube Design

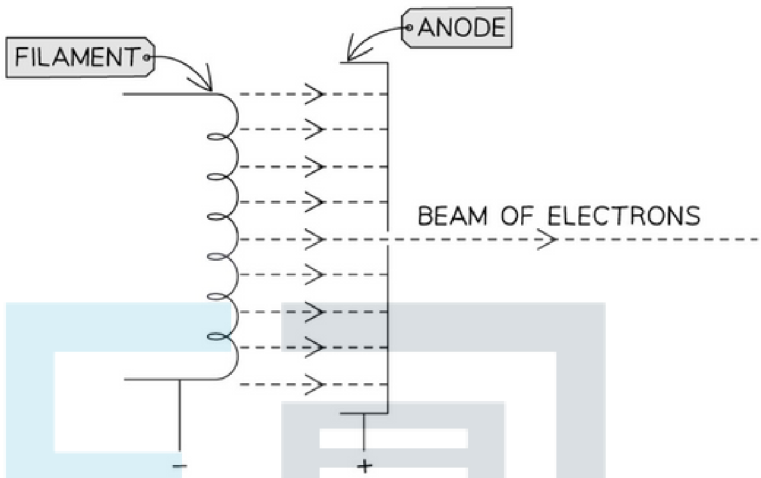


The filament is heated, giving electrons enough energy to be easily removed. All electrons are accelerated towards the anode's positive charge - some pass through a hole in the centre, forming a tight beam of electrons.

Worked Example

Figure 1 shows a thin filament placed near an anode with a hole in it. Passing current through the filament generates a beam of electrons.

Figure 1



Explain why passing a current through the filament causes the emission of electrons.

Answer:

Step 1: Recall that thermionic emission requires a heated cathode (filament)

- The current heats the wire

Step 2: Explain why this higher temperature is needed

- The electrons in the filament gain enough kinetic energy to escape the filament and accelerate towards the anode

Exam Tip

Remember that current passing through a wire causes it to heat up – it is the higher temperature, not the current, that gives the electrons enough energy to be easily attracted from the cathode towards the anode.

Work Done on an Electron

- Using the concept of work done, the **speed** of electrons in a cathode ray tube can be calculated
- Work done, *W*, by an electric field of potential difference, *V*, on a charge, *q*, is equal to:

$$W = qV$$

- For an electron:

$$W = eV$$

- In this instance, all work done on an electron is transferred to its kinetic store, and we can assume their initial velocity is near-zero so:

$$W = E_k$$

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

- where m_e is electron mass and v is the speed of the electron

Worked Example

An electron is accelerated through a vacuum by an electric field with a potential difference of 500 V. It exits through a small hole in a positive plate.

Calculate its speed upon leaving the electric field.

Answer:

Step 1: List the known quantities:

- Electron mass, $m_e = 9.11 \times 10^{-31}$ kg
- Magnitude of the charge of an electron, e = 1.60×10^{-19} C
- Potential difference, $V = 500$ V

Step 2: Recall the equation relating work done on an electron and kinetic energy

- To determine electron speed, v:

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

Step 3: Rearrange this equation to make velocity the subject

- Multiply both sides by 2, divide both by mass and square root both sides to get:

$$v = \sqrt{\frac{2eV}{m_e}}$$

Step 4: Substitute the known quantities

- For the final answer:

$$v = \sqrt{\frac{2 \times (1.60 \times 10^{-19}) \times 500}{9.11 \times 10^{-31}}} = 1.33 \times 10^{7}\ \mathrm{m\,s^{-1}}$$

Exam Tip

This same concept of *work done = kinetic energy* is referred to again in Bertozzi's Experiment at the end of the Special Relativity section, so make sure you are familiar with this idea before moving on.

12.1.3 Specific Charge

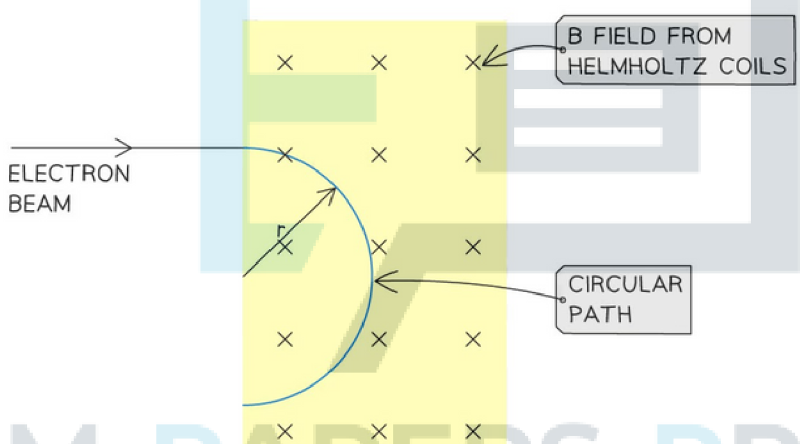
Determining the Specific Charge of an Electron

- Specific charge is the charge per unit mass of an object - this has units of C kg^{-1}
  - For an electron, this is $\frac{e}{m_e}$, where e is the charge of an electron and m_e is the mass of an electron
- You need to be able to describe how specific charge is determined using:
  - A magnetic field only
  - A magnetic field and an electric field
  - An electric field only

Determining Specific Charge with A Magnetic Field Only

- When moving in a magnetic field, a charge experiences a force perpendicular to its motion

Diagram showing circular path in magnetic field only



The radius of the electron beam's circular path can be measured to calculate specific charge

- Recall for a circular path of radius *r* with electrons of mass m_e moving at a speed *v*, the centripetal force *F* is:

$$F = \frac{m_e v^2}{r}$$

- For a magnetic force, F_B, from a field with flux density *B* on a charge of magnitude e :

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- This magnetic force **is** the centripetal force so we can equate the two equations above and write as an expression for *v* :

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- Recall from Thermionic Emission that work done on electrons by an anode of potential difference V_A can be equated to their kinetic energy:

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- By substituting the expression for speed from above, we can determine the specific charge (try deriving this yourself):

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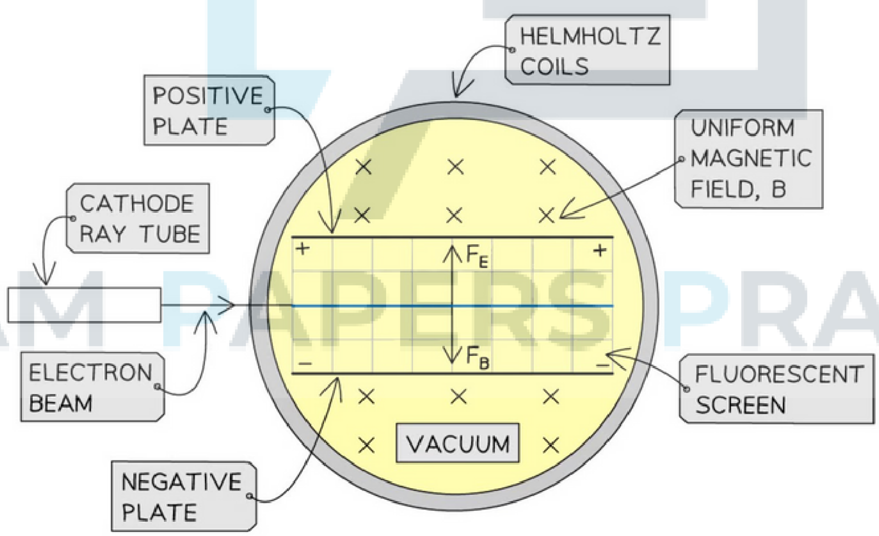
- The terms V_A, r, and B can all be measured, so this experiment allows the specific charge of the electron to be determined

Balancing Electric and Magnetic Fields

- The method J.J. Thomson used to determine the specific charge of an electron, balanced magnetic and electric forces on a beam of electrons
  - A piece of apparatus called Helmholtz coils generates a magnetic field
  - Oppositely charged plates generate an electric field

A diagram showing the balanced forces from Helmholtz coils and an electric field



The magnetic field generates a downward force, the electric field between the plates generates an upward force – the fluorescent screen shows a straight beam when these two forces are equal and opposite

- In this diagram, the Helmholtz coils' magnetic field points into the plane of the page, exerting a downward magnetic force F_B (you can verify this with the left-hand rule)
- The electric field strength, E, can be varied by changing the potential difference V across the plates (separated by distance d) until the electric force, F_E, is equal to F_B:

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- Recall that the force from the electric field can be calculated using the charge on the electron, *e* :

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- For magnetic flux density *B* and electron velocity *v*, magnetic force is:

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- Equating the two forces allows us to determine electron speed:

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- The electric field was then switched off, and the beam formed a circular path, allowing the equation from the magnetic field only method to be used:

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- Combining these two equations gave Thomson the expression:

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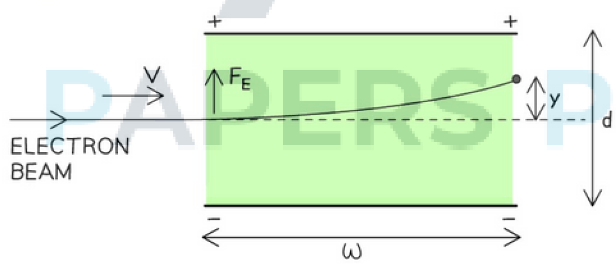
- The terms *V* , *r* , *B* and *d* can all be measured, so this experiment allowed the specific charge of the electron to be determined

Specific Charge using an Electric Field Only

- This method uses constant acceleration equations for the beam of electrons passing through an electric field

Trajectory of electron beam in electric field



The horizontal speed of the electrons remain constant, but they have a constant acceleration vertically

- This can be treated like a standard trajectory problem - time *t* of the path is calculated using the horizontal speed *v* and width of the plates *w* :

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- Now considering the vertical plane, the upwards acceleration *a* can be calculated using *F* = *ma* :

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- Constant acceleration equations can also be used in the vertical plane for another expression for acceleration:

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  - Initial velocity is 0 ms^{-1} vertically, therefore ut = 0
  - Displacement, s, can be measured (see y on the diagram)
  - Time, t, is given by the first expression above
  - Therefore:

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- Speed can be calculated by equating work done and kinetic energy, as in the magnetic field method, and acceleration can be calculated once y and w are measured
  - This means specific charge can once again be determined if we rearrange this expression for a :

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  - To give:

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Worked Example

A group of students are unsure of the magnetic flux density generated by an old set of Helmholtz coils from their school.

Using a pair of charged plates of known separation with a known potential difference across them and the Helmholtz coils, they form a straight beam coming from an electron gun. They do not know the potential difference across the electron gun.

Their teacher reminds them of the following equations:

$$\text{specific charge of an electron} = \frac{v}{rB}$$

$$v = \frac{V}{Bd}$$

Their teacher also reminds them of their AQA data booklets.

Explain what else they must do to determine the magnetic flux density of the Helmholtz coils.

Answer:

Step 1: List the quantities the students know

- The students know:
  - Potential difference, *V*
  - Separation of the plates, *d*
- The students need to find the term *B*

Step 2: Describe how the students can determine the missing quantities

- The students need the radius *r* of the electron beam in the electric field
- They can turn off the electric field and measure the radius of the circular path of the electrons
- Specific charge of an electron is the magnitude of an electron's charge divided by its mass
- Both quantities can be found in their data booklets

Step 3: Explain how they can use this to determine *B*

- The students must now rearrange the given equations to make *B* the subject and substitute their values

Exam Tip

You must be prepared to answer questions and perform calculations on all three methods, but you only need to be able to recall the method for one of the three methods. The magnetic field method has appeared regularly in past papers so this may be a sensible choice.

Comparing Specific Charge

- Thomson demonstrated the deflected particles in magnetic and electric fields must be **negatively charged**
- Previously, scientists had calculated the specific charge of a hydrogen ion (which as we now know, is a proton)
- Thomson's specific charge for an electron was around **1800 times larger** than that of the hydrogen ion, as shown in the table below

Specific charges of the electron and the hydrogen ion

	Specific Charge ($C\,kg^{-1}$)
Electron	1.76×10^{11}
Hydrogen Ion	9.6×10^{7}

Thomson's Experiment

- Recall that specific charge is defined as:

$$\frac{\text{particle charge}}{\text{particle mass}}$$

- The fact that this number for an electron was much larger than for a hydrogen ion meant either:
  - The electron had a much smaller mass
  - The electron had a much larger magnitude of charge
- Specific charge is a ratio so there was no way of knowing which was correct
  - Further experiments had to be performed to calculate the charge of an electron

12.1.5 Millikan's Oil Drop Experiment

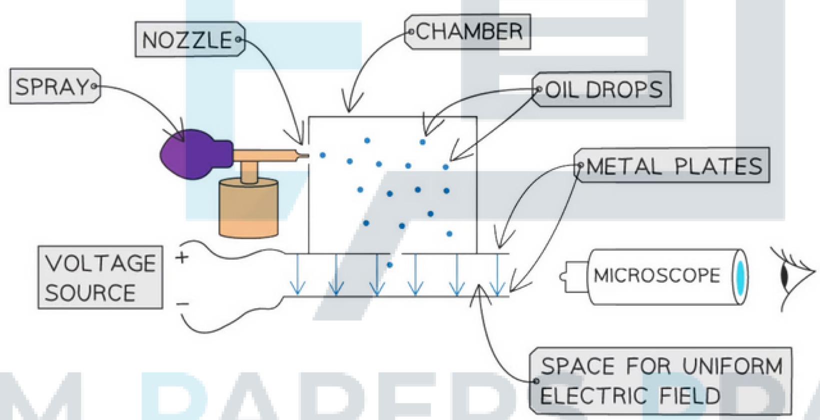
Millikan's Oil Drop Experiment

- This experiment was conducted by Millikan and Fletcher in 1909
- It determined the value of fundamental or elementary charge

Method for Millikan's Oil Drop Experiment

- A fine mist of **atomised oil drops** is sprayed into a chamber
  - Oil is used instead of water because it does not evaporate quickly
  - This means the **mass** of the drops will remain **constant**
- As the drops pass out of the spray nozzle they are ionised by **X-rays**
  - This consequently changes their charge from neutral
  - They will become positively charged if they lose electrons
  - They will become negatively charged if they gain electrons
- The drops pass into a region between **two metal plates** and are viewed using a **microscope**

Equipment Set Up for Millikan's Oil Drop Experiment



In Millikan's Oil Drop Experiment oil is sprayed into a chamber before passing between metal plates where the electric and gravitational forces are compared

Condition for Stationary Oil Drops

- The charged oil drops fall into a uniform electric field between plates separated by distance d with potential difference V
  - Negative oil drops with magnitude of charge Q experience an upward force from the uniform electric field
  - The magnitude of this force F is:

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

- The falling oil drops can be held **stationary** between the plates by increasing this upward force

- For this to occur, the force *F* has to be equal to the weight of the oil drop, *mg*, so there is no resultant vertical force on each drop

- Therefore, the condition under which oil drops are held stationary is:

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

- The aim of the experiment, however, was to determine the charge Q of each oil drop
  - For that, Milikan needed to determine the **mass** of each oil drop, so he used Stokes' Law

Worked Example

One particular oil drop had a mass of 5.1×10^{-15} kg. It is held stationary between two charged plates. These are separated by 12 mm and there is a potential difference of 1250 V across them.

Calculate the charge of the oil drop.

Answer:

Step 1: List the known quantities:

- Mass, $m = 5.1 \times 10^{-15}$ kg
- Separation of plates, d = 12 mm
- Potential difference, V = 1250 V
- Acceleration due to gravity, $g = 9.81$ m s^{-2}

Step 2: Recall the condition for a stationary oil drop:

- The condition for the oil drop not to fall or rise:

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

Step 3: Rearrange this equation to calculate charge:

- Make charge the subject:

$$Q = \frac{mgd}{V} = \frac{(5.1 \times 10^{-15}) \times 9.81 \times (12 \times 10^{-3})}{1250}$$

$$Q = 4.8 \times 10^{-19}\ \text{C}$$

Exam Tip

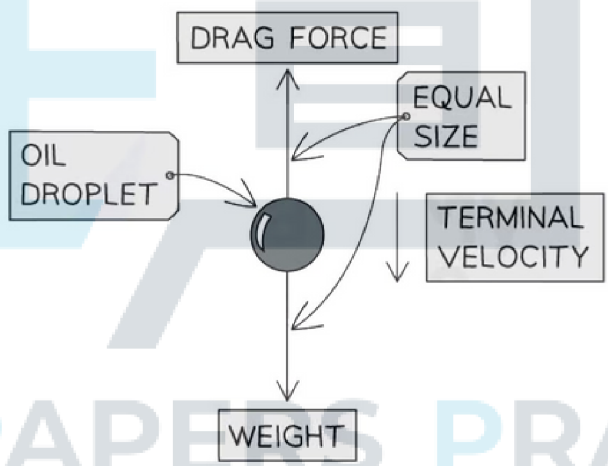
The condition for a stationary oil droplet is given in the equation sheet. Focus your revision on **using** it and understanding where it comes from, as opposed to memorising the equation.

Motion of a Falling Oil Droplet

Motion of the Oil Droplet without the Electric Field

- Millikan's experiment was designed to determine the charge of oil droplets, and therefore the charge on electrons
    - To calculate charge using the condition for stationary oil droplets, however, the mass of each oil droplet was required
- With the electric field turned off, the oil droplets fell at **terminal velocity**
    - This means their weight, *mg*, was balanced by drag forces as they passed through the air
    - Millikan timed the oil drops as they passed the window of his apparatus to determine their **speeds**

A diagram showing weight and drag forces on an oil droplet



At terminal velocity, speed is constant and resultant force is zero, so weight is balanced by drag forces

Stokes' Law

Viscous Drag Force using Stokes' Law

- In fluid dynamics, Stokes' law allows drag force on an object through a fluid (such as air) to be calculated, provided:
  - The object is small
  - The object is spherical
  - The speed is low
- Stokes' law states that, for an object with radius *r* moving at velocity *v* through a fluid with viscosity η, the viscous drag force, *F*, is:

$$F = 6\pi\eta rv$$

Calculating Mass from Stokes' Law

- Recall that the drag force and weight are equal at terminal velocity, so:

$$6\pi\eta rv = mg$$

- Both mass and radius are unknown, but we can write mass in terms of radius for a sphere of known density, ρ:

$$m = \rho V = \frac{\rho 4\pi r^3}{3}$$

- Combining these equations allowed Millikan to determine the radius, and therefore mass, of an oil drop whose velocity was known
  - Recall the condition for a stationary oil drop:

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

  - This now gave Millikan enough information to calculate the charge Q on an oil drop if he knew its terminal velocity and the potential difference *V* required to make it stationary

Significance of Millikan's Results

- Millikan repeated his experiment for many different oil droplets
  - They all had different charges, but he noticed an interesting pattern in his results
  - Every value of charge was an integer multiple of 1.60×10^{-19} C

Table of results from Millikan's Experiment

Oil Droplet Number	Charge on Droplet ($\times 10^{-19}$ C)	Charge divided by 1.60×10^{-19} C
1	1.59	0.994
2	11.1	6.94
3	9.54	5.96

4	15.9	9.94
5	6.36	3.98

Millikan's results showed that the charge on each oil drop was an integer multiple of 1.60×10^{-19} C

Quantisation of Electric Charge

- Each negative oil droplet had been ionised, so carried an integer number of electrons
  - The fact that each droplet's charge was quantised into integer multiples of 1.60×10^{-19} C suggested that this was the charge of each electron

Worked Example

Using Stokes' Law, show that the droplet's mass m can be expressed in terms of its velocity v, the viscosity of air η, the density of the oil ρ and acceleration due to gravity g, as:

$$\frac{6\pi\eta v}{g}\sqrt{\frac{9\eta v}{2\rho g}}$$

Answer:

Step 1: Write down the relevant equation from the data and formulae sheet

- Stokes' law:

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

Step 2: Apply Stokes' law to the droplet at terminal velocity

- At terminal velocity (in the absence of an electric field), weight is equal to viscous drag force:

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

Step 3: Write mass in terms of radius and density

- We need to get rid of the radius term as it will not be in our final expression
  - We can do this by writing radius in terms of the required quantities
- Recall the equation relating mass, density and volume of a sphere, V_s:

$$m = V_s \rho$$

$$m = \frac{4\pi r^3 \rho}{3}$$

Step 4: Write an expression for the droplet's radius

- Substitute the expression for mass in terms of radius and density and rearrange for radius:

$$\frac{4\cancel{\pi} r^{\cancel{3}\,2} \rho g}{3} = 6\cancel{\pi}\eta \cancel{r} v$$

$$r^2 = \frac{9\eta v}{2\rho g}$$

$$r = \sqrt{\frac{9\eta v}{2\rho g}}$$

Step 5: Substitute this into the expression for mass

- We can finally eliminate radius from the equation in step 2:

$$m = \frac{6\pi\eta r v}{g}$$

$$m = \frac{6\pi\eta v}{g}\sqrt{\frac{9\eta v}{2\rho g}}$$

Exam Tip

"Show that" questions are one of the rare moments in an exam you can be totally confident you have the correct answer, but don't get complacent. The marks are awarded for **clear** and **logical** working out. Don't try to skip a step and hope you can convince your examiner, be thorough.