OCR A Level Physics

E.m.f & Internal Resistance

Your notes

Contents

E.m.f & Internal Resistance

E.m.f & Internal Resistance

- When charge passes through a power supply such as a battery, it **gains** electrical energy

- The **electromotive force (e.m.f)** is the amount of **chemical** energy converted to **electrical** energy per **coulomb** of charge **(C)** when charge passes through a power supply

$$E.M.F. = \frac{ENERGY\ TRANSFORMED\ FROM\ OTHER\ FORMS\ TO\ ELECTRICAL}{CHARGE}$$

- E.m.f can be represented by the symbol ε (greek letter epsilon)

    - It is not actually a force, and is measured in **volts (V)**

- The e.m.f source is from a **battery** or a **power supply**

- E.m.f is equal to the potential difference across the cell when no current is flowing

- E.m.f can be measured by connecting a high-resistance voltmeter around the terminals of the cell in an open circuit, as so:
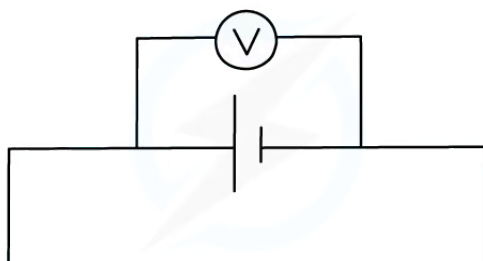
*e.m.f is measured using a voltmeter connected in parallel with the cell*

Internal Resistance

- All power supplies have some resistance between their terminals

    - This is called **internal resistance** (*r*)

- It is internal resistance that causes the charge circulating to dissipate some electrical energy from the power supply itself

  - This is why the cell becomes warm after a period of time

- Therefore, over time the internal resistance causes **loss of voltage** or energy loss in a power supply

- A cell can be thought of as a source of e.m.f with an internal resistance connected in series. This is shown in the circuit diagram below:
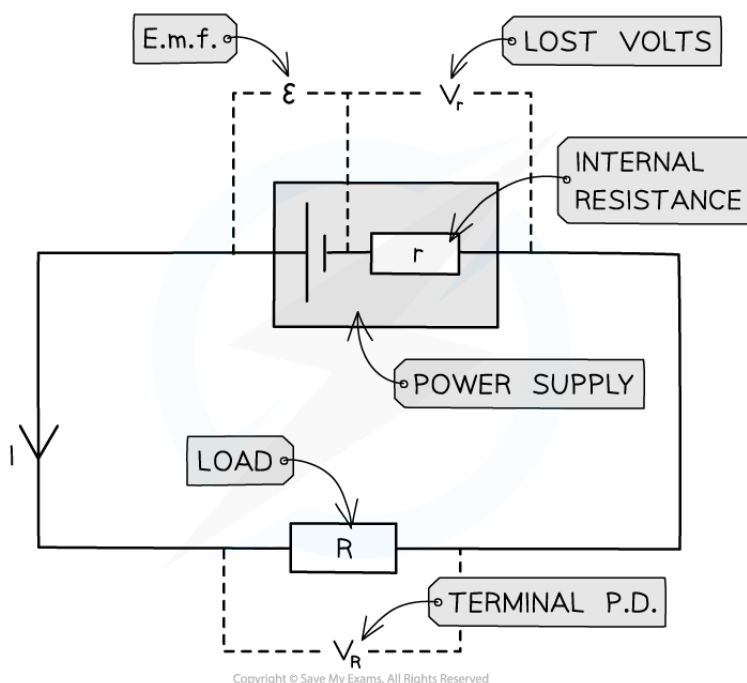
Circuit showing the e.m.f and internal resistance of a power supply

- Where:

  - Resistor R is the 'load resistor'

  - r is the internal resistance

  - ε is the e.m.f

  - V_r is the lost volts

  - V_R is the p.d across the load resistor, which is the same as the terminal p.d

Terminal p.d & Lost Volts

- The **terminal potential difference (p.d)** is the potential difference across the terminals of a cell

- If there was no internal resistance, the terminal p.d would be equal to the e.m.f
- It is defined as:

$$V = IR$$

- Where:

  - V = terminal p.d (V)

  - I = current (A)

  - R = resistance (Ω)

- If a cell has internal resistance, the terminal p.d is always **lower** than the e.m.f

- If you have a load resistor R across the cell's terminals, then the terminal p.d V **also** the p.d across the load resistor

- In a closed circuit, current flows through a cell and a potential difference develops across the internal resistance

- Since resistance opposes current, this reduces the energy per unit charge (voltage) available to the rest of the external circuit

- This difference is called the 'lost volts'

  - **Lost volts** is usually represented by little v

  - It is defined as the voltage **lost** in the cell due to internal resistance, so, from conservation of energy:

  - v = e.m.f – terminal p.d

$$v = \varepsilon - V = Ir \text{ (Ohm's law)}$$

- Where:

  - v = lost volts (V)

  - I = current (A)

  - r = internal resistance of the battery (Ω)

  - ε = e.m.f (V)

  - V = terminal p.d (V)

- Therefore, lost volts is the **difference** between the e.m.f and the terminal p.d

Examiner Tips and Tricks

If the exam question states 'a battery of negligible internal resistance', this assumes that e.m.f of the battery is equal to its voltage. Internal resistance calculations will not be needed here.If the battery in the circuit diagram includes internal resistance, then the e.m.f equations must be used.

Your notes

Calculating E.m.f

Calculating E.m.f

- The e.m.f ε is defined by the equation:

- E.m.f can therefore be defined as the **total**, or **maximum**, voltage available to the circuit

Worked Example

A battery of e.m.f 7.3 V and internal resistance r of 0.3 Ω is connected in series with a resistor of resistance 9.5 Ω.
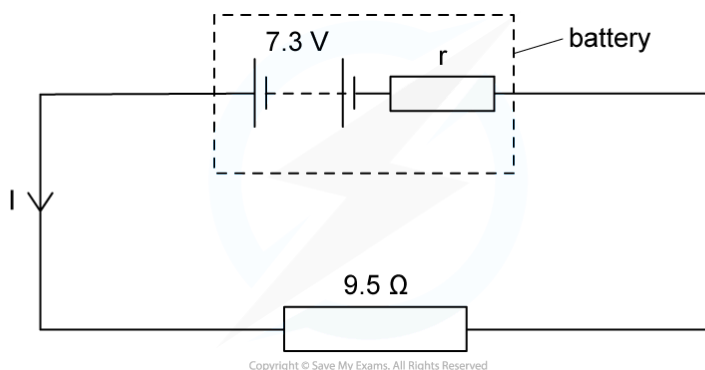
Determine:

a) The current in the circuit

b) Lost volts from the battery

Answer:

a.)

STEP 1
USING THE e.m.f EQUATION TO DETERMINE THE CURRENT I
$$\varepsilon = I(R + r)$$

STEP 2
REARRANGE FOR I
$$I = \frac{\varepsilon}{(R + r)}$$

STEP 3
SUBSTITUTE IN THE VALUES
$$I = \frac{7.3}{(9.5 + 0.3)} = 0.745... = 0.7\,A \quad (2\ s.f.)$$

b.)

STEP 1
THE LOST VOLTS IS THE VOLTAGE LOST DUE TO INTERNAL RESISTANCE
$$LOST\ VOLTS = I \times r$$

STEP 2
SUBSTITUTE IN THE VALUES
$$LOST\ VOLTS = 0.7 \times 0.3 = 0.21 = 0.2V \quad (2\ s.f.)$$

Your notes

Your notes

Determining Internal Resistance

Aims of the Experiment

The overall aim of the experiment is to investigate the relationship between e.m.f and internal resistance by measuring the variation of current and voltage using a variable resistor

Variables

- Independent variable = resistance, R (Ω)

- Dependent variable = voltage, V (V) & current, I (A)

- Control variables:

  - E.m.f of the cell

  - Internal resistance of the cell

Equipment List

| Apparatus	Purpose
1.5 V Cell	To provide an e.m.f. to the circuit
Resistor	Unknown resistance — to act as internal resistance
100Ω Variable Resistor	To change the values of current and voltage in the circuit
Voltmeter	0–2 V range — to measure voltage
Ammeter	0–200 mA range — to measure current
Wires	At least 6 leads — to make electrical connections
Switch	To open between readings to not run down the battery

- Resolution of measuring equipment:

  - Voltmeter = 1 mV

  - Ammeter = 0.1 mA

Method
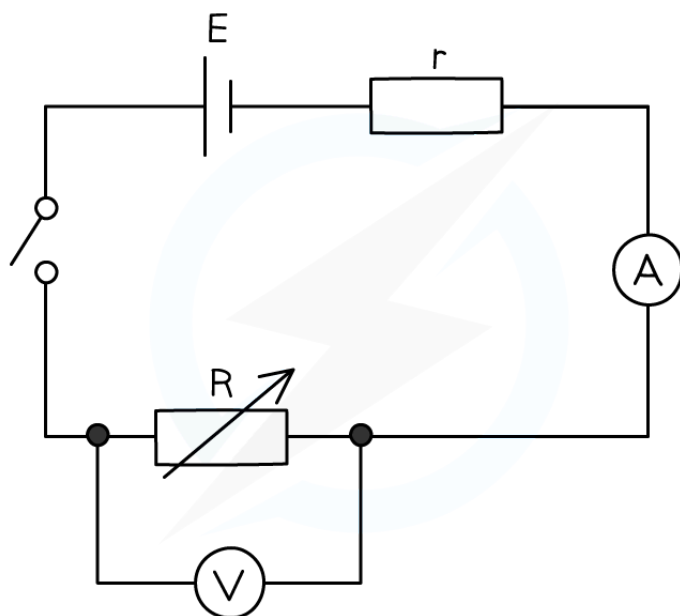
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1. The cell and the resistor, labelled *r*, should be connected in series and considered to be a single cell

2. With the switch open, record the reading *V* on the voltmeter

3. Set the variable resistor to its maximum value, close the switch and record *V* and the reading *I* on the ammeter - make sure to open the switch between readings

4. Vary the resistance of the variable resistor up to a minimum of 8–10 readings and record values for *V* and *I* for each resistance. Ensure to take readings for the whole range of the variable resistor

▪ An example of a suitable table might look like this:

Your notes

RESISTANCE OF VARIABLE RESISTOR	VOLTMETER READING				AMMETER READING			
	1st READING		2nd READING		3rd READING		MEAN	
R / Ω	V/V	I/mA	V/V	I/mA	V/V	I/mA	V/V	I/mA
0								
10								
20								
30								
40								
50								
60								
70								
80								
90								
100								

Analysing the Results

- The relationship between e.m.f. and internal resistance is given by

$$\varepsilon = I\,(R + r)$$

- Where:

  - ε = electromotive force (V)

  - I = current (A)

  - R = resistance of the load in the circuit (Ω)

  - r = internal resistance of the cell (Ω)

- This can be simplified into the form:

$$\varepsilon = IR + Ir = V + Ir$$
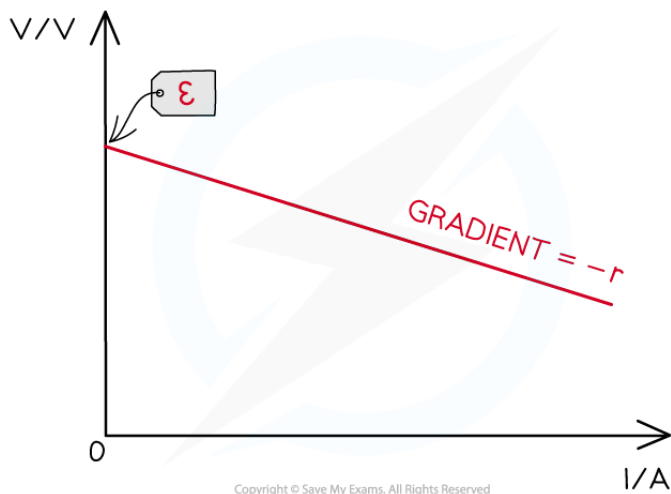
- Rearranging this equation for V:

$$V = -rI + \varepsilon$$

- Comparing this to the equation of a straight line: y = mx + c

    - $y = V$ (V)

    - $x = I$ (A)

    - Gradient = $-r$ (Ω)

    - Y-intercept = ε (V)

1. Plot a graph of V against I and draw a line of best fit

2. Measure the gradient of the graph and compare it with the manufacturer's value of the resistor

3. The y-intercept will be the e.m.f and the gradient will be the negative internal resistance:

Evaluating the Experiment

Systematic Errors:

- Only close the switch for as long as it takes to take each pair of readings

    - This will prevent the internal resistance of the battery or cell from changing during the experiment

Random Errors:

- Only use fairly new cells otherwise the e.m.f. and internal resistance of run-down batteries can vary during the experiment

- Wait for the reading on the voltmeter and ammeter to stabilise (stop fluctuating) before recording the values

- Take multiple repeat readings (at least 3) for each voltage and current and calculate a mean to reduce random errors

Safety Considerations

- This is a very safe experiment, however, electrical components can get hot when used for a long period

- Switch off the power supply right away if burning is smelled

- Make sure there are no liquids close to the equipment, as this could damage the electrical equipment

✏️

Worked Example

In an experiment, a student uses a variable resistor as an external load. The current flowing through the circuit is measured with a suitable milliammeter and the potential difference across the variable resistor is measured with a voltmeter for a range of resistance values. The data collected was as follows:

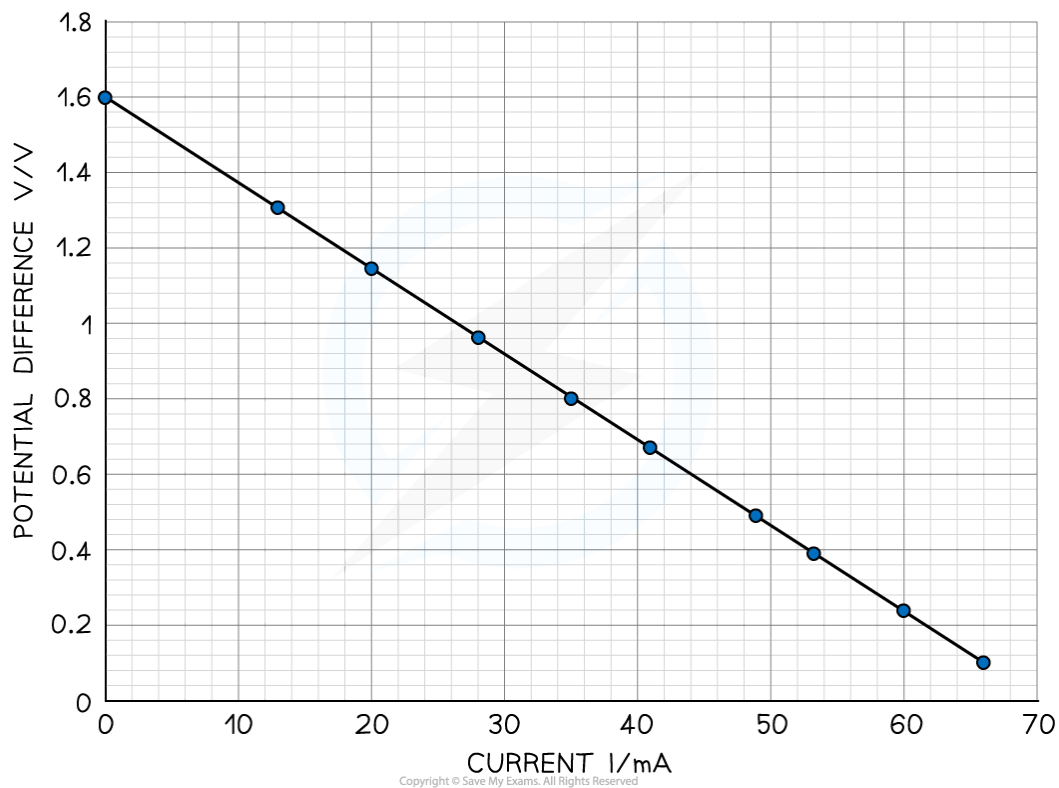| V/V	I/mA
1.60	0.0
1.30	13.1
1.14	20.0
0.96	28.2
0.80	35.2
0.65	41.5
0.49	48.8
0.38	53.4
0.23	60.3
0.10	66.0

Plot a graph of these results and determine the e.m.f. and the internal resistance directly from the graph.
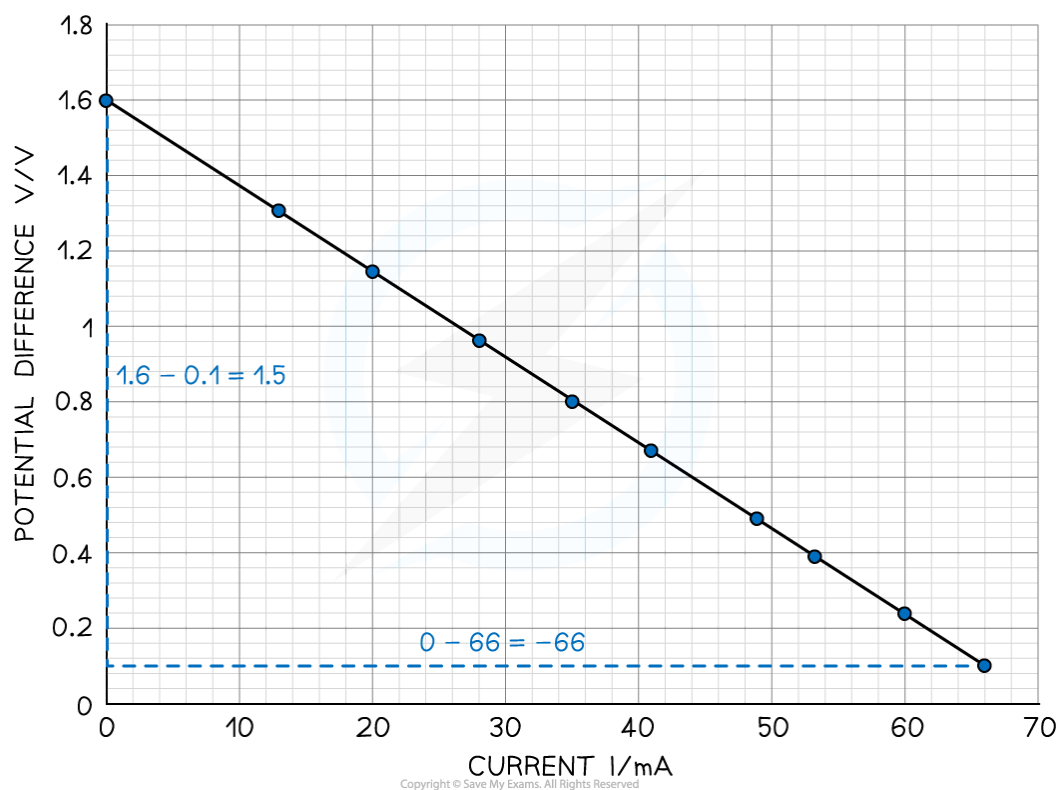
Answer:

Step 1: Plot the data on a graph of *V* against *I* and draw a line of best fit

Step 2: Draw the largest triangle possible in order to calculate the gradient

Your notes

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$$\text{Gradient} = \frac{\Delta y}{\Delta x} = \frac{1.6 - 0.1}{-66 \times 10^{-3}} = -22.7 \ \Omega \ (3 \text{ s.f.})$$

Step 3: Determine the e.m.f. and the internal resistance from the graph

$$V = -rI + E$$

- From this equation:

  - Gradient = $-r$ (Ω)
  - Y-intercept = E (V)
- Therefore:

 - Internal resistance, r = 22.7 Ω
  - E.m.f. E = 1.60 V
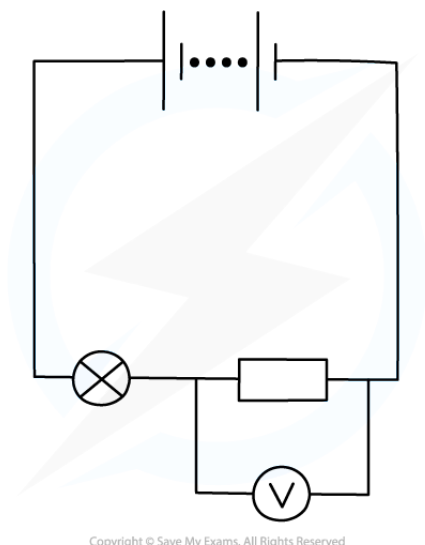
E.m.f & Potential Difference

Potential Difference (p.d.)

- A cell makes one end of the circuit positive and the other negative

  - This sets up a **potential difference** (p.d) across the circuit

- The potential difference across a component in a circuit is defined as

  The energy transferred per unit charge flowing from one point to another

- The energy transfer is from electrical energy into other forms

- Potential difference is measured in **volts (V)**. This is the same as a **Joule per coulomb (J C^{-1})**

  - If a bulb has a voltage of 3 V, every coulomb of charge passing through the bulb will lose 3 J of energy

- The potential difference of a power supply connected in series is always shared between all the components in the circuit
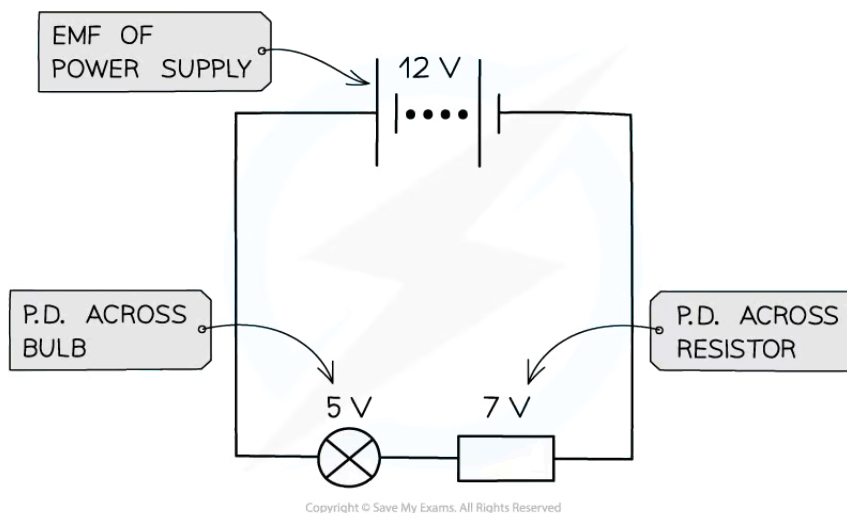
The potential difference is the voltage across each component in a circuit

- Potential difference or voltage is measured using a **voltmeter**

- A voltmeter is always set up in parallel to the component you are measuring the voltage for

Potential difference can be measured by connecting a voltmeter in parallel between two points in a circuit

E.m.f & Potential Difference

- The difference between **potential difference** and **e.m.f** is the type of energy transfer per unit charge

$$P.D. = \frac{ENERGY\ TRANSFORMED\ FROM\ ELECTRICAL\ TO\ OTHER\ FORMS}{CHARGE}$$

- When charge passes through a resistor, for example, its electrical energy is converted to heat in the resistor

  - The resistor, therefore, has a **potential difference** across it

- Potential difference describes the loss of energy from charges

  - Ie. when **electrical energy** is **transferred** to other forms of energy in a component

- E.m.f. describes the **transfer of energy** from the **power supply** to **electrical charges** within the circuit

Examiner Tips and Tricks

Although voltage and potential difference are the same thing, make sure not to confuse them with e.m.f, which is slightly different!

| Energy Transfer | Your notes |

Energy Transfer in Circuits

- E.m.f is defined as the **energy transferred by the power supply per unit charge**

- This energy transformed is also equal to the **work done** by the moving charge

- This is defined by the equation:

$$W = εQ$$

- Where:

  - W = work done / energy transferred (J)

  - $ε$ = e.m.f (V)

  - Q = charge (C)

- The potential difference is the **energy transferred to the electrical component per unit charge**

- This means the equation can also be written as:

$$W = VQ$$

- Where:

  - V = potential difference (V)

- These equations show that

$$1\,V = 1\,J\,C^{-1}$$

Worked Example

An electric kettle requires 0.4 MJ to be supplied to boil a cup of water. The e.m.f. of the mains supply is 230 V. Calculate the charge supplied.

Answer:

Step 1: List the known quantities

- Energy transferred (work done), W = 0.4 MJ = 0.4×10^6 J

  - E.m.f, $ε$ = 230 V

Step 2: Write the relevant equation

$$W = \varepsilon Q$$

Step 3: Rearrange for charge, Q

$$Q = W \div \varepsilon$$

Step 4: Substitute in the values

$$Q = (0.4 \times 10^6) \div 230 = 1739.13 = \textbf{1700 C}$$

Energy Transfer for Charged Particles

- A dynamo or battery transfer energy to each charge carrier, which are electrons in metals, as they pass through

  - Each electron has a charge of e

- Since the energy transferred (work done) W is defined as

$$\boldsymbol{W = QV}$$

- Then:

$$\boldsymbol{W = eV}$$

- Where the charge Q is now replaced with the charge of the electron e

- 1 eV is 1 **electronvolt**, which is defined as:

  A unit of energy equal to the work done by an electron accelerated through a potential difference of 1 volt

- When a potential difference is applied across a conductor, the electrons are accelerated and gain kinetic energy

Your notes

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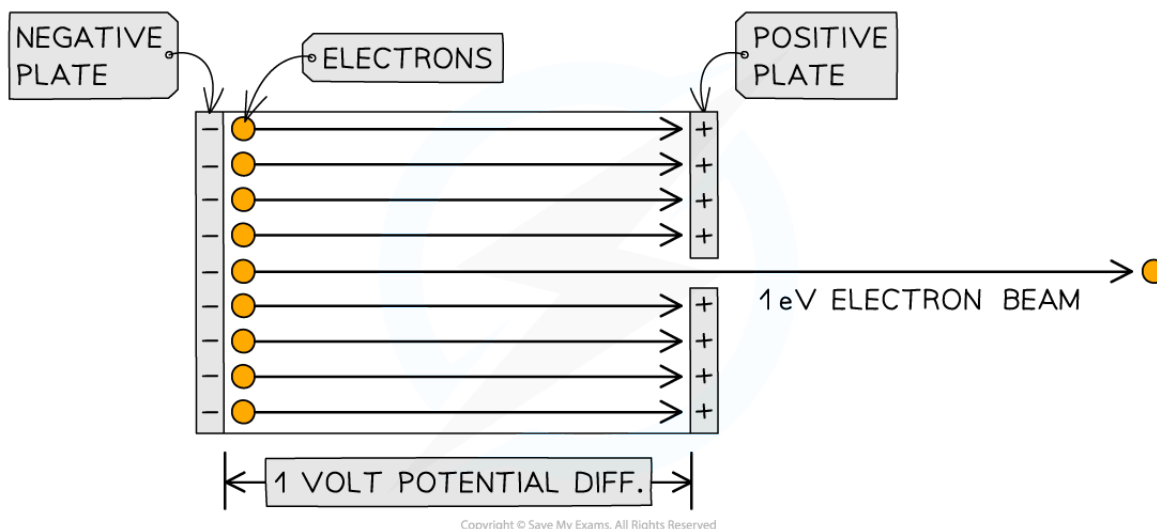
Electron beam accelerated through a potential difference of 1 V

- This kinetic energy gained is equal to an electronvolt:

$$eV = \tfrac{1}{2}mv^2$$

- Where:

    - e = elementary charge (C)

    - *V* = potential difference (V)

    - m = mass of the electron (kg)

    - *v* = speed of the electrons (m s^{-1})

- To convert between eV and J:

    - eV → J: **multiply** by 1.6×10^{-19}

    - J → eV: **divide** by 1.6×10^{-19}

Worked Example

Calculate the speed of an electron that is accelerated through a potential difference of 5 V.

Answer:

Step 1: List the known quantities

- Charge of an electron, $e = 1.6 \times 10^{-19}$ C (from data sheet)
- Potential difference, $V = 5$ V
- Electron rest mass, $m = 9.11 \times 10^{-31}$ kg (from data sheet)

Step 2: Write the relevant equation

$$eV = \frac{1}{2}mv^2$$

Step 3: Rearrange for the speed, v

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

Step 4: Substitute in the values

$$v = \sqrt{\frac{2 \times \left(1.6 \times 10^{-19}\right) \times 5}{9.11 \times 10^{-31}}} = \mathbf{1.33 \times 10^6 \text{ m s}^{-1}}$$

Examiner Tips and Tricks

Remember to clearly state the difference between lower case v meaning velocity and upper case V meaning the potential difference in your exam, otherwise, you may define or substitute the wrong value!