

• Candidates should be able to :

- State that **electric fields** are created by **electric charges**.
- Define **electric field strength** as force per unit positive charge.
- Describe how **electric field lines** represent an electric field.

- Select and use Coulomb's law in the form :

$$F = \frac{Qq}{4\pi\epsilon_0 r^2}$$

- Select and apply the equation for the electric field strength of a point charge :

$$E = \frac{Q}{4\pi\epsilon_0 r^2}$$

- Select and use the equation for the magnitude of the uniform electric field strength between charged, parallel Plates :

$$E = \frac{V}{d}$$

- Explain the **effect of a uniform electric field on the motion of charged particles**.
- Describe the **similarities and differences** between the **gravitational fields** of point masses and the **electric fields** of point charges.

- An **ELECTRIC FIELD** is a region which exists around particles and objects which have an **ELECTRIC CHARGE**.
- Any particle or object which is electrically charged will experience a **FORCE** when placed in an electric field.

The **ELECTRIC FIELD STRENGTH (E)** at a point in an electric field is the **FORCE PER UNIT POSITIVE** charge exerted by the field at that point.

$$E = \frac{F}{Q}$$

(N C<sup>-1</sup>)                      (N)                      (C)

**NOTE**

- The **FORCE (F)** exerted on a **CHARGE (Q)** at a point where there is an **ELECTRIC FIELD STRENGTH (E)** is given by :

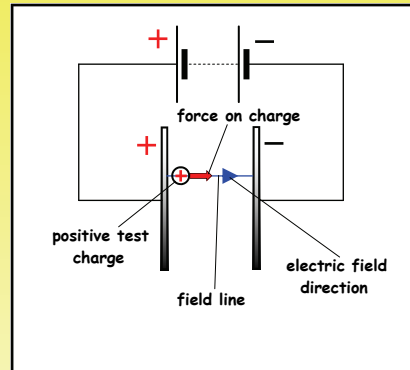
$$F = QE$$

- **ELECTRIC FIELD STRENGTH (E)** is a **vector** quantity and so E-values must be treated **vectorially** (i.e. direction as well as magnitude must be taken into account) when calculating the **resultant E** due to a number of charges.
- Electric field strength,                       $E = F/Q$   
Gravitational field strength,                       $g = F/m$

**ELECTRIC FIELD LINES**

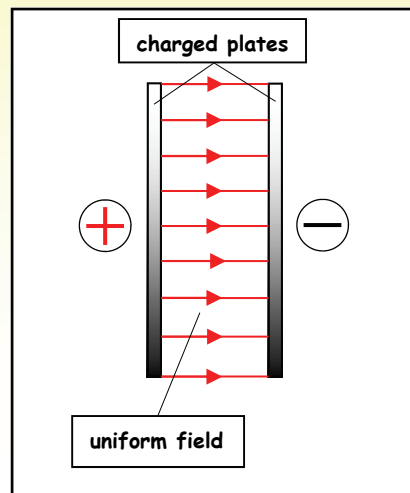
- **FIELD LINES** (sometimes called **LINES OF FORCE**) are used to give a visual representation of an electric field.

- The field line gives the direction along which a positive test charge will move when placed in the field.



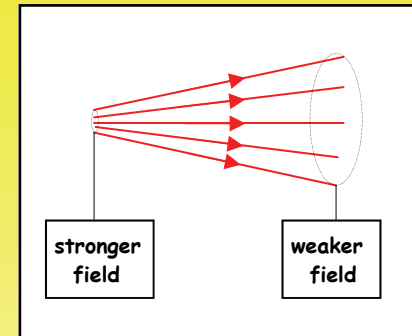
In the diagram opposite, the electric field between the plates forces the positive test charge to move from left to right as it is repelled by the positively charged plate on the left and attracted by the negatively charged plate on the right.

- A **UNIFORM** electric field is represented by **parallel, equidistant** field lines.

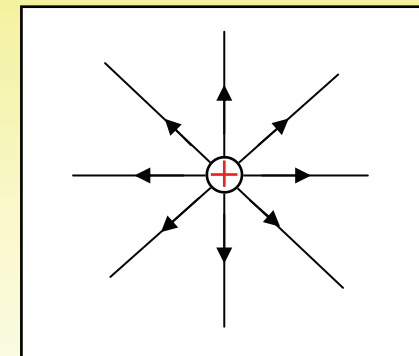


This shows that the electric field strength is constant in magnitude and direction.

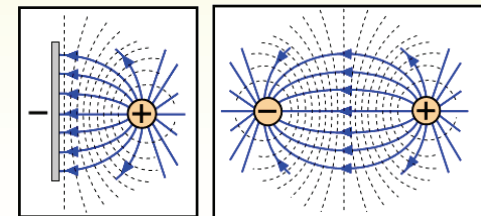
- **Non-parallel** field lines are used to represent a **NON-UNIFORM** electric field, **diverging** field lines indicating a **weakening** field and **converging** field lines indicating a **strengthening** field.



- The electric field around a point charge is called a **RADIAL FIELD**. The field lines **diverge**, showing that the **electric field strength decreases with distance**.



- The diagrams opposite show :  
(a) The field between a positive charge and a negatively charged metal plate.



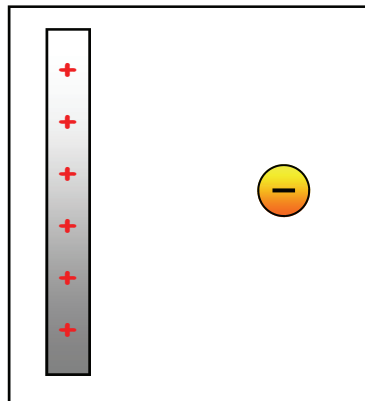
- (b) The field between opposite charges.

• PRACTICE QUESTIONS (1)

- 1 (a) Define **electric field strength (E)**.
- (b) What **direction** does the arrow on an electric field line indicate?
- (c) Using diagrams to illustrate your answers, explain what is meant by:
- A **uniform** electric field.
  - A **non-uniform** electric field.
  - A **radial** electric field.

- 2 The diagram opposite shows a negatively charged metal sphere placed close to a positively charged metal plate.

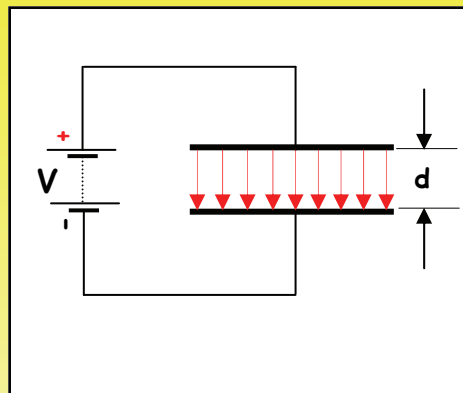
Copy the diagram and draw the electric field lines between the sphere and the plate. Indicate the direction of the field lines.



- 3 (a) Calculate the magnitude of the **field strength** at a point in an electric field if a test charge of  $+2.8 \mu\text{C}$  placed at the point experiences a force of  $84 \text{ mN}$ .
- (b) A dust particle having a charge of  $9.6 \times 10^{-19} \text{ C}$  is at a point in an electric field where the field strength is  $3.0 \times 10^5 \text{ N C}^{-1}$ . Calculate the magnitude of the **force** on the dust particle and state its **direction**.

STRENGTH OF A UNIFORM ELECTRIC FIELD

A **UNIFORM ELECTRIC FIELD** is obtained between two parallel metal plates which are **distance (d)** apart and have a **potential difference (V)** between them.



The field lines are :

- Parallel to each other.
- At right angles to the plates.
- Directed from the positive plate to the negative plate.

The **FIELD STRENGTH (E)** is increased by :

- Increasing the potential difference (V).
- Decreasing the plate separation (d).

The **FIELD STRENGTH (E)** is given by :

$$E = \frac{-V}{d}$$

(V m<sup>-1</sup>)                      (V)                      (m)

**NOTE**

- The negative sign in the equation indicates that
- The **FORCE (F)** acting on a **CHARGE (Q)** when it is placed in the **UNIFORM ELECTRIC FIELD** of strength (E) between the plates is given by :

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

(N)                      (C)                      (m)                      (V)

- The unit of **ELECTRIC FIELD STRENGTH (E)** may be :

- newton per coulomb ( $\text{N C}^{-1}$ ), OR
- volt per metre ( $\text{V m}^{-1}$ ).

The link between the two units can be seen from  $F = QE = QV/d$

Rearranging the equation gives :  $F/Q = V/d = E$

$$\text{N C}^{-1} = \text{V m}^{-1}$$

### COULOMB'S LAW

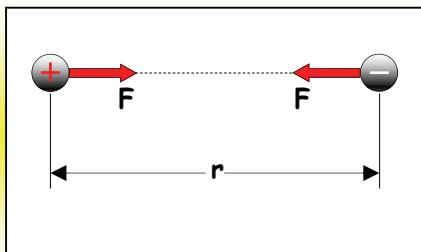
**COULOMB'S LAW** states that any two charged particles exert a force on each other that is **directly proportional to the product of their charges** and **inversely proportional to the square of their distance apart**.

For two charges, ( $Q_1$ ) and ( $Q_2$ ), distance ( $r$ ) apart, in a vacuum (or air), the **FORCE (F)** which they exert on each other is :

$$F \propto \frac{Q_1 Q_2}{r^2}$$

$$F = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2}$$

(C) (C)  
(F m<sup>-1</sup>) (m)



### NOTE

- $1/4\pi\epsilon_0$  is the constant of proportionality =  $8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$ .
- $\epsilon_0$  is the **PERMITTIVITY OF A VACUUM** =  $8.85 \times 10^{-12} \text{ F m}^{-1}$ .
- Permittivity of air ( $\epsilon_{\text{air}}$ )  $\approx$  Permittivity of a vacuum ( $\epsilon_0$ ).

### PRACTICE QUESTIONS (2)

- DATA :**
  - $\epsilon_0 = 8.85 \times 10^{-12} \text{ F m}^{-1}$
  - $1/4\pi\epsilon_0 = 9.0 \times 10^9 \text{ m F}^{-1}$
  - Electron charge,  $e = 1.6 \times 10^{-19} \text{ C}$

- Calculate the force between an electron and :
  - a proton at a distance of  $2.5 \times 10^{-9} \text{ m}$ ,
  - a nucleus of a nitrogen atom (charge  $+7e$ ) at a distance of  $2.5 \times 10^{-9} \text{ m}$ .
- A  $+30 \text{ nC}$  point charge is at a fixed distance of  $6.2 \text{ mm}$  from a point charge  $Q$ . The charges attract each other with a force of  $4.3 \times 10^{-2} \text{ N}$ .
  - Calculate the **magnitude of charge Q** and state whether  $Q$  is a **positive** or **negative** charge.
  - The two charges are moved  $2.5 \text{ mm}$  further apart. Calculate the **force** between them in this new position.

3 (a) Two point charges  $Q_1 = +6.3 \text{ nC}$  and  $Q_2 = -2.7 \text{ nC}$  exert a force of  $3.2 \times 10^{-5} \text{ N}$  on each other when they are at a distance,  $d$  apart. Calculate :

(i) The **distance,  $d$** , between the two charges,

(ii) The **force** between the two charges if they are moved to a distance =  $3d$  apart.

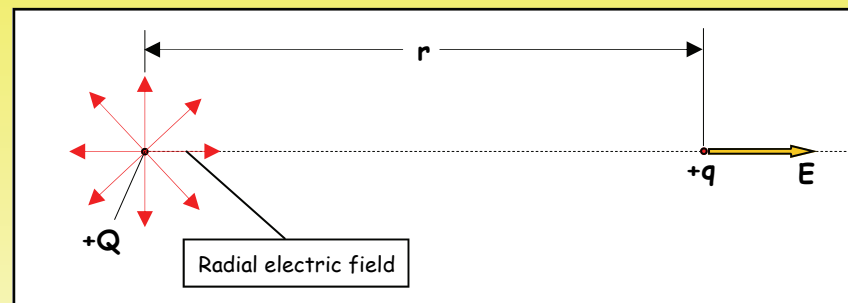
(b) A charge of  $+4 \text{ nC}$  is added to each charge in (a). Calculate the force between  $Q_1$  and  $Q_2$  when they are at separation  $d$ .

4 Use the data given below to calculate the magnitude of the **ELECTRIC** and **GRAVITATIONAL** forces acting between the proton and the electron in an atom of hydrogen.

- Average proton-electron separation,  $r = 5.0 \times 10^{-11} \text{ m}$ .
- Electron (and proton) charge,  $e = 1.6 \times 10^{-19} \text{ C}$ .
- Electron mass,  $m_e = 9.1 \times 10^{-31} \text{ kg}$ .
- Proton mass,  $m_p = 1.7 \times 10^{-27} \text{ kg}$ .
- $G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$
- $1/4\pi\epsilon_0 = 8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$

### ELECTRIC FIELD STRENGTH DUE TO A POINT CHARGE

- A **POINT CHARGE** is an expression used for a charged object in a situation where the distances under consideration are much greater than the size of the object.
- A **TEST CHARGE** in an electric field is a point charge which does not alter the electric field in which it is placed.



Consider the electric field due to a point charge  $+Q$  as shown in the diagram above.

The **force ( $F$ )** on a test charge  $+q$  placed at a **distance ( $r$ )** from  $+Q$  is :

$$F = \frac{Qq}{4\pi\epsilon_0 r^2}$$

And since  $E = F/q$  (By definition),

$$E = \frac{Q}{4\pi\epsilon_0 r^2}$$

(C)

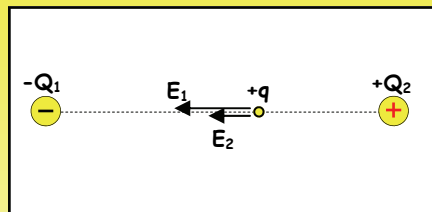
(V m<sup>-1</sup> or N C<sup>-1</sup>)
(F m<sup>-1</sup>)
(m)

- NOTE that electric field strength is a **VECTOR** quantity and so has to be treated **VECTORIALLY** when solving problems involving more than one charge.

**Examples**

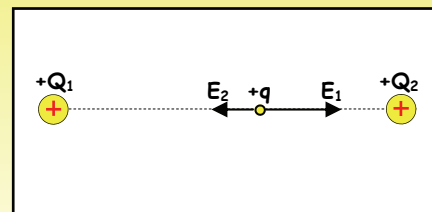
- E* in the same direction.**  
The *E*-values are added.

$$E_R = E_1 + E_2$$



- E* in opposite direction.**  
The *E*-values are subtracted.

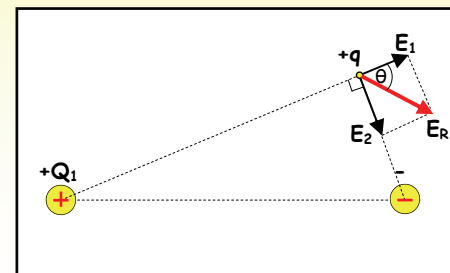
$$E_R = E_1 - E_2$$



- E* at right angles.**  
The problem must be resolved by treating the *E*-values as you would treat any vectors at  $90^\circ$  to each other.

$$E_R = \sqrt{E_1^2 + E_2^2}$$

$$\theta = \tan^{-1} \frac{E_2}{E_1}$$



- PRACTICE QUESTIONS (3)**

- 1 (a) Calculate the **electric field strength** at a distance of **3.2 mm** from a **+6.0 nC** point charge.
- (b) Calculate the **distance** from the point charge in (a) at which the electric field strength is  **$5.4 \times 10^5 \text{ V m}^{-1}$** .

- 2 A **+25  $\mu\text{C}$**  point charge  **$Q_1$**  is at a distance of **60 mm** from a **+100  $\mu\text{C}$**  charge  **$Q_2$** . A **+15 pC** charge  **$q$**  is placed at **M**, **25 mm** from  **$Q_1$**  and **35 mm** from  **$Q_2$** .

(a) Calculate : (i) The **resultant** electric field strength at **M**,

(ii) The magnitude and direction of the **force** on  **$q$** .

(b) Show that the **resultant** electric field strength due to  **$Q_1$**  and  **$Q_2$**  is **zero** at a point which is **20 mm** from  **$Q_1$**  and **40 mm** from  **$Q_2$** .

- 3 An isolated metal sphere of radius **0.3 m** has a charge of  **$-4.0 \times 10^{-6} \text{ C}$**  evenly distributed on its surface. Calculate :

(a) The **electric field strength** at the surface of the sphere.

(b) The **distance** from the sphere's surface at which the electric field strength is  **$150 \text{ kV m}^{-1}$** .

- 4 An iron atom has a nucleus that contains **26 protons** (and a lot of neutrons). Its electrons orbit at a typical distance of  **$10^{-10} \text{ m}$** .

(a) Calculate the attractive **force** exerted by the nucleus on a single electron at this distance.

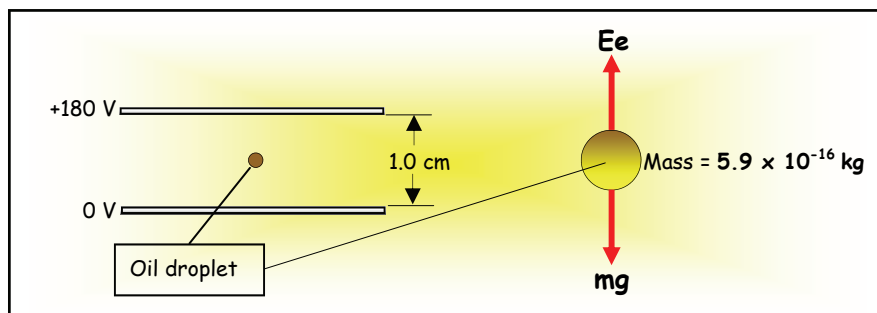
(b) The nucleus of an iron atom has a diameter of  **$4.9 \times 10^{-15} \text{ m}$** . Calculate the **electric field strength** :

(i) Where the electrons are.

(ii) At the surface of the nucleus.

## 5 MEASUREMENT OF THE ELECTRONIC CHARGE 'e'

The charge 'e' of an electron is very small ( $-1.6 \times 10^{-19} \text{ C}$ ) and difficult to measure. The American Physicist **Robert Millikan** devised an ingenious method to find 'e'. He used tiny droplets of oil, charged by friction, and suspended in a uniform electric field.

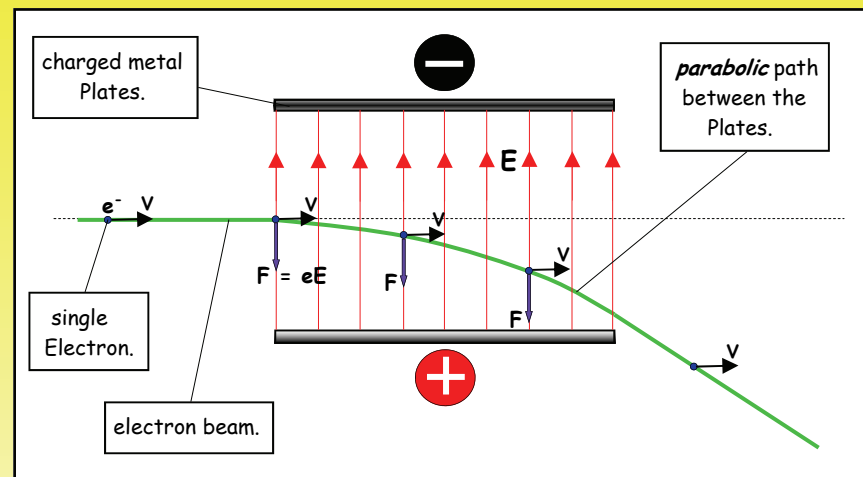


If a particular droplet was stationary, he knew that the electric force acting on it upwards was equal to the force of gravity acting downwards on it. He managed to find the weight of these tiny droplets by measuring their terminal velocity as they fell through the air, another ingenious part of his technique.

Study the diagrams, and use the information to answer the questions below.

- The upper plate in the diagram is connected to the **positive** terminal of the supply. What does this tell you about the **sign of the charge** on the droplet?
- What is the **electric field strength** between the plates?
- What is the **weight** of the droplet?
- What is the **electric force** acting on the droplet when it is **stationary**?
- What is the **charge** on the droplet? What is the significance of this value?
- In Millikan's experiment, he included a source of  **$\beta$ -radiation** (This kind of radiation is simply electrons). When an oil droplet was irradiated, it was suddenly observed to start moving **upwards**. Explain this effect.
- Assuming that the charge on the oil droplet had increased because it had captured a **single electron**, what new value of **voltage** between the plates would be needed to hold the droplet **stationary**?

## MOTION OF CHARGED PARTICLES IN A UNIFORM ELECTRIC FIELD



- When a beam of electrons enters the space between two parallel, charged metal plates, an **electric field force (F)** acts on each electron. The **force (F)** is given by:

$$F = eE$$

Electron charge
electric field strength

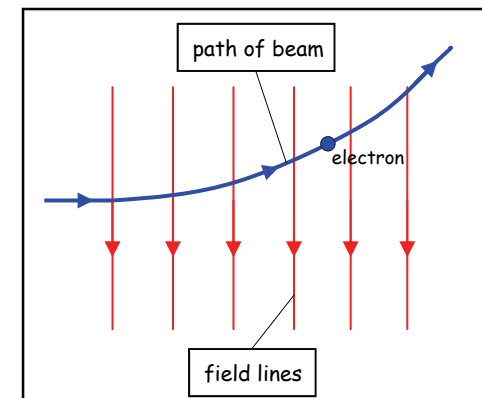
- Force (F)** acts at **90°** to the direction of motion of the electron and so has no effect on this motion.
- The sideways acceleration given to each electron by the force (F) plus the forward velocity (v) causes the electron to follow a **parabolic path** while it travels between the plates. This is equivalent to the parabolic path followed by a body projected horizontally from a cliff-top, the difference being that in this case the force is that due to gravity.

## COMPARING GRAVITATIONAL AND ELECTRIC FIELDS

	Gravitational Field	Electric Field
<b>SIMILARITIES</b>		
Field Line or Line of Force	Path of a free test mass in the field	Path of a free test charge in the field
Inverse square law of force	Newton's Law of Gravitation $F = G m_1 m_2 / r^2$	Coulomb's Law of Force $F = Q_1 Q_2 / 4\pi\epsilon_0 r^2$
Field Strength	Force per unit mass $g = F/m$	Force per unit + charge $E = F/Q$
Unit of Field Strength	$N\ kg^{-1}$ or $m\ s^{-2}$	$N\ C^{-1}$ or $V\ m^{-1}$
Uniform Fields	$g$ is constant Field lines are parallel	$E$ is constant Field lines are parallel
Radial Fields	Due to a point mass ( $M$ ) $g = -GM/r^2$	Due to a point charge ( $Q$ ) $E = Q/4\pi\epsilon_0 r^2$
<b>DIFFERENCES</b>		
Action at a distance	Between any two masses	Between any two charged objects
Force	Attraction only	Unlike charges attract, Like charges repel
Constant of proportionality in Force Law	$G = 6.67 \times 10^{-11}\ N\ m^2\ kg^{-2}$	$\frac{1}{4\pi\epsilon_0} = 8.99 \times 10^9\ N\ m^2\ C^{-2}$

- 1 (a) An electron is situated in a uniform electric field. The electric force that acts on it is  $8 \times 10^{-16}\ N$ . If the charge on an electron is  $-1.6 \times 10^{-19}\ C$ , calculate the **strength of the electric field**.
- (b) Calculate the **acceleration** of an electron ( $e = -1.6 \times 10^{-19}\ C$ ) in a television tube where the electric field strength is  $8.0 \times 10^6\ V\ m^{-1}$ .

- 2 A beam of electrons is directed horizontally into a uniform electric field which acts vertically downwards, as shown in the diagram opposite.

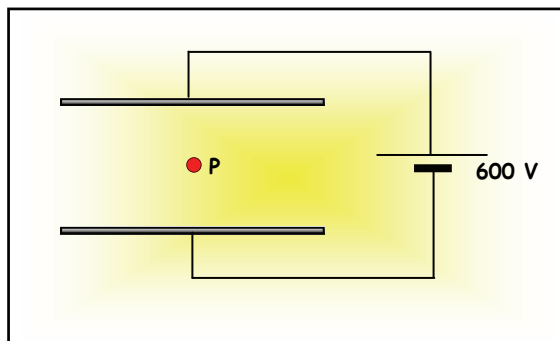


- (a) **Explain** why the beam follows a path which **curves upwards**.
- (b) Each electron in the beam experiences a constant force of  $1.8 \times 10^{-13}\ N$ . Calculate the **strength of the electric field**.



• HOMEWORK QUESTIONS

- 1 A nitrogen atom is initially stationary at point P as shown in the diagram opposite, midway between two large, horizontal parallel plates in an evacuated chamber. The nitrogen atom becomes charged.

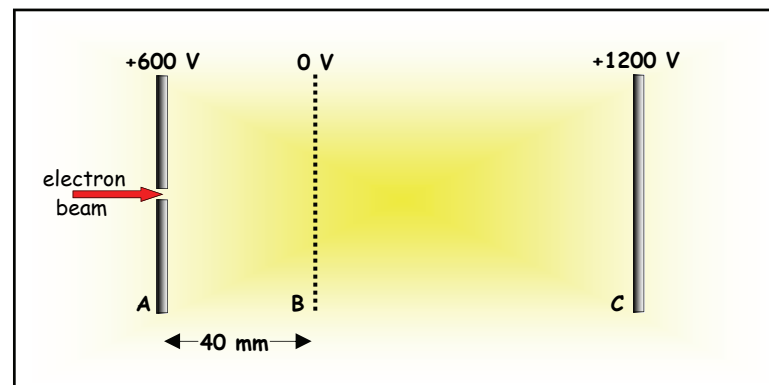


There is an electric field between the plates. Ignore any effects of gravity.

- (a) The direction of the electric force on the nitrogen ion is **vertically downwards**. State with a reason the sign of the charge on the ion.
- (b) The voltage between the plates is **600 V**. At the instant that the ion, charge  $1.6 \times 10^{-19} \text{ C}$  and mass  $2.3 \times 10^{-26} \text{ kg}$ , reaches the lower plate, show that :
- (i) The **kinetic energy** of the ion is  $4.8 \times 10^{-17} \text{ J}$ .
- (ii) The **speed** of the ion is  $6.5 \times 10^4 \text{ m s}^{-1}$ .
- (c) The electric field strength between the plates is  $4.0 \times 10^4 \text{ N C}^{-1}$ . Calculate the **separation** of the plates.

(OCR A2 Physics - Module 2824 - June 2006)

- This question is about changing the motion of electrons using electric fields. The diagram below shows a horizontal beam of electrons moving in a vacuum. The electrons pass through a hole in the centre of a metal plate A. At B is a metal grid through which the electrons can pass. At C is a further metal sheet. The three vertical conductors are maintained at voltages of **+600 V** at A, **0 V** at B and **+1200 V** at C. The distance from plate A to grid B is **40 mm**.

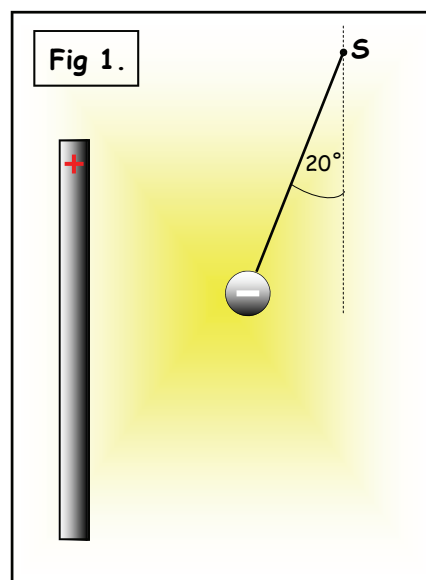


- (a) Copy the diagram and draw **electric field lines** to represent the fields in the regions between the three plates.
- (b) Show that the magnitude of the **electric field strength** between plate A and grid B is  $1.5 \times 10^4 \text{ V m}^{-1}$ .
- (c) Calculate the **horizontal force** on an electron after passing through the hole in A.
- (d) Show that the **minimum speed** that an electron in the beam must have at the hole in A to reach the grid at B is  $1.5 \times 10^7 \text{ m s}^{-1}$ .
- (e) Calculate the **speed** of these electrons when they collide with sheet C.
- (f) **Describe and explain** the effect on the **current** detected at C when the voltage of the grid B is **increased negatively**.

(OCR A2 Physics - Module 2824 - January 2005)

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- 3 This question is about electric forces. A very small, **negatively** charged conducting sphere is suspended by an insulating thread from support **S**. It is placed close to a vertical metal plate carrying a **positive** charge. The sphere is attracted towards the plate and hangs with the thread at an angle of  $20^\circ$  to the vertical as shown in **Fig 1**.



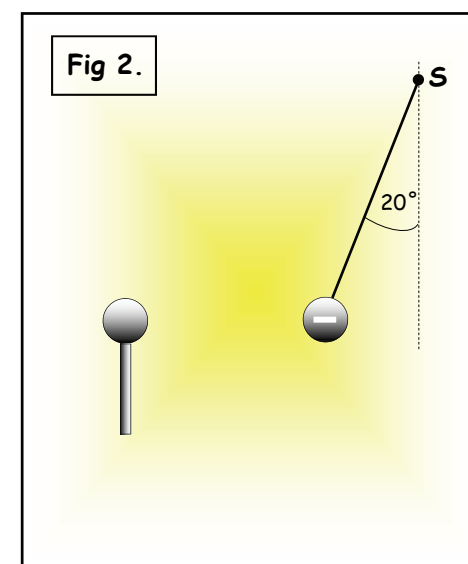
- (a) Draw at least **five** electric field lines on **Fig 1**. to show the pattern of the field between the plate and the sphere.
- (b) The sphere of weight  $1.0 \times 10^{-5} \text{ N}$  carries a charge of  $-1.2 \times 10^{-9} \text{ C}$ .
- (i) Show that the magnitude of the attractive **force** between the sphere and the plate is about  $3.6 \times 10^{-6} \text{ N}$ .
- (ii) Hence show that the value of the **electric field strength** at the sphere, treated as a **point charge**, is  $3.0 \times 10^3$  in **SI units**. Also **state the unit**.

- (c) The plate is removed.

Fig 2. shows an identical sphere carrying a charge of  $+1.2 \times 10^{-9} \text{ C}$  mounted on an insulating stand.

It is placed so that the hanging sphere remains at  $20^\circ$  to the vertical.

Treating the spheres as point charges, calculate the **distance,  $r$**  between their centres.



- (d) On **Fig 2.**, sketch the **electric field pattern** between the two charges.

By comparing this sketch with your answer to (a), suggest why the distance between the plate and the sphere in **Fig 1**. is **half** of the distance between the two spheres in **Fig 2**.