Topic 25: Charged Particles

Content:

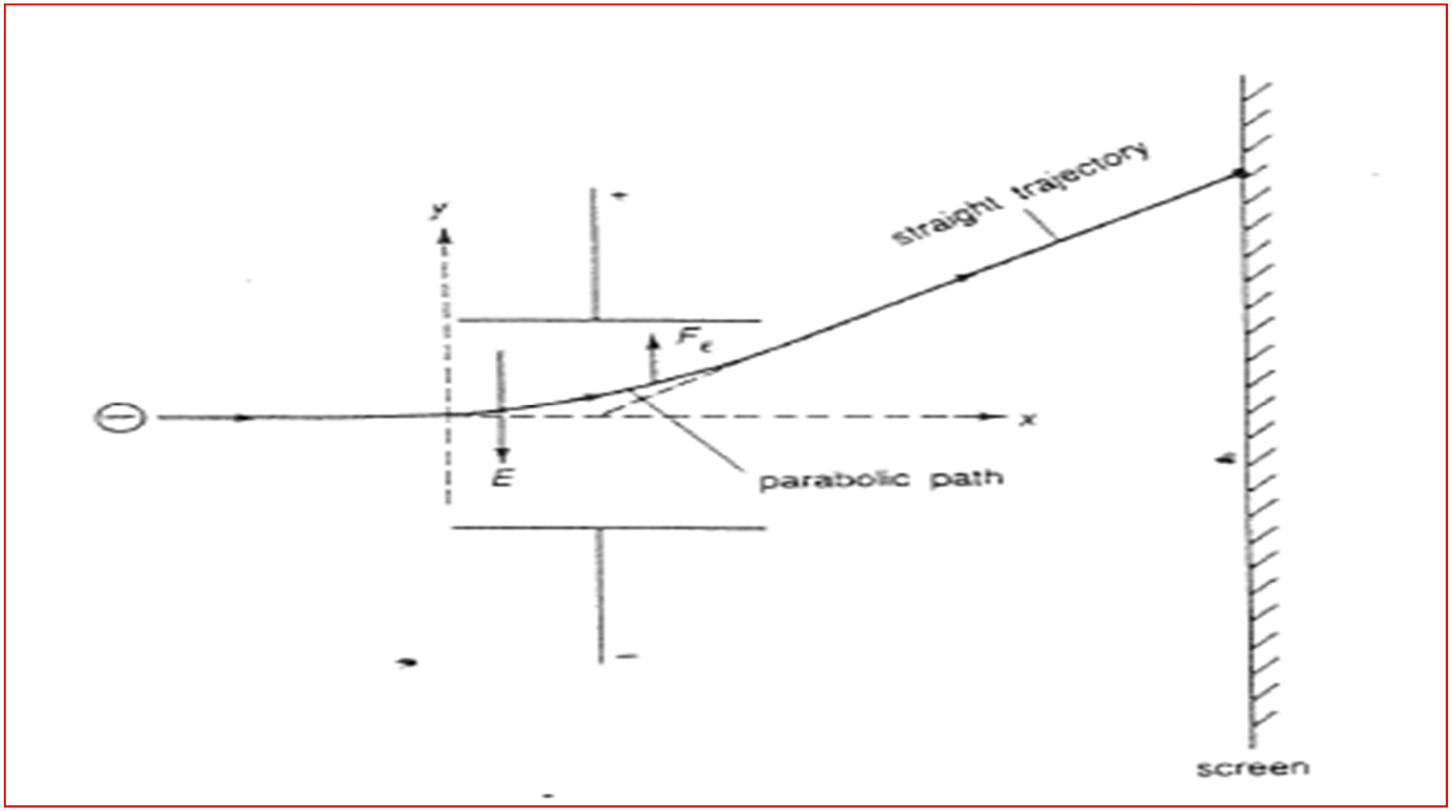
25.1 Electrons

25.2 Beams of charged particles

Introduction

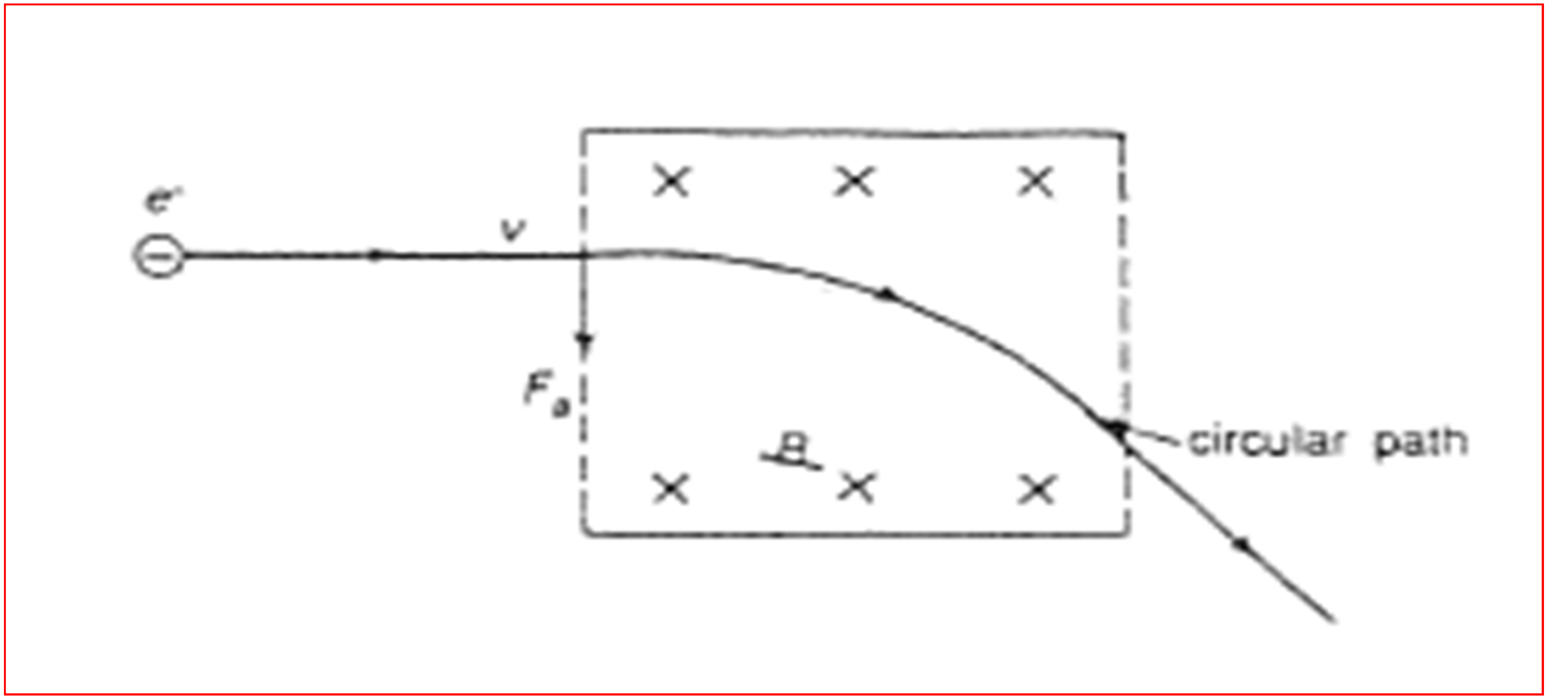
- Charged particles which are in motion are generally influenced by electric and magnetic fields.
- We will look at how charged particles behave in these fields, and how this knowledge can be used to control beams of charged particles.
- We will also look at how this knowledge was used to discover the electron and to measure its charge and mass.

Principle of Electron deflection



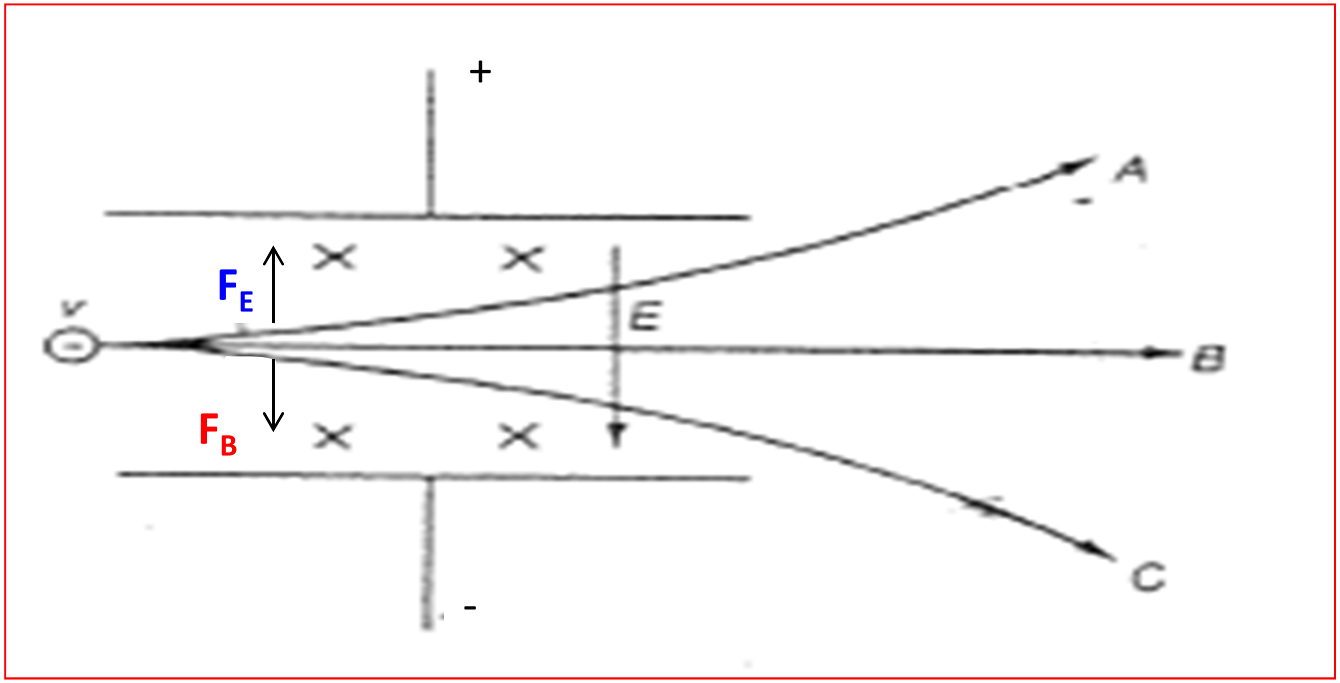
- ***Due to Electric Field only***
- **Electric force, F = qE**
- **But E = V / d (uniform E field)**
- **Thus, F = qV / d**

Principle of Electron deflection



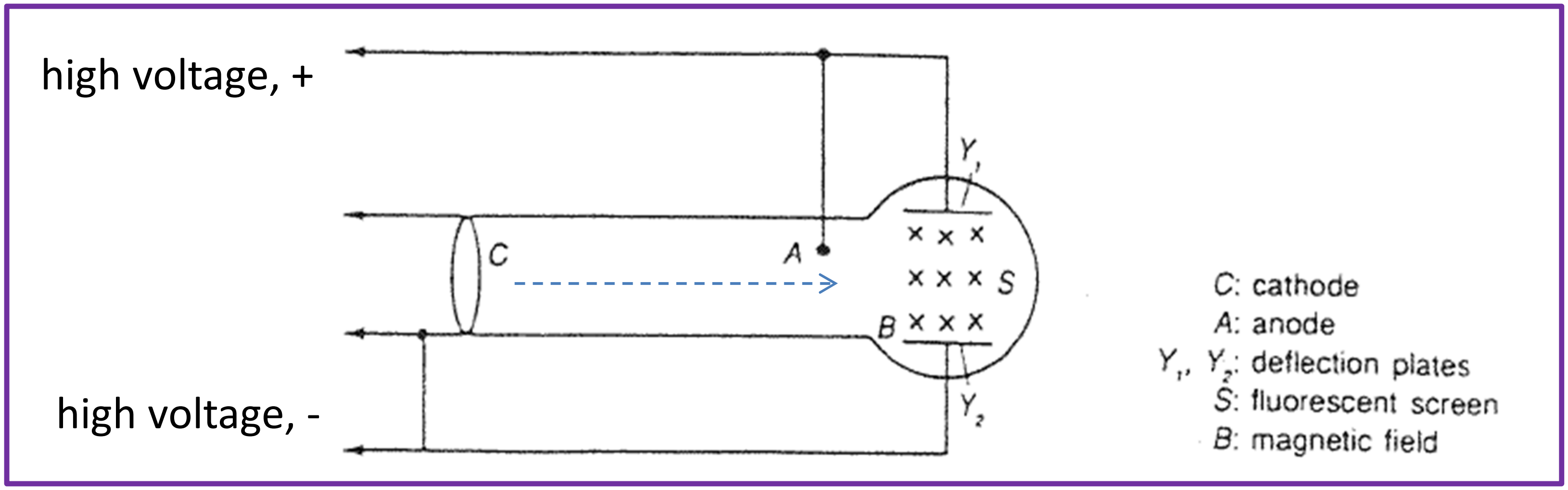
- ***Due to Magnetic Field only.***
- **Magnetic force, $F = Bqv = mv^2 / r \rightarrow r = mv / Bq$**
- Take note: Unlike the electric force, the magnetic force cannot change the energy of the electron. It deflects the electron, but does not change its speed or K.E.

Principle of Electron deflection



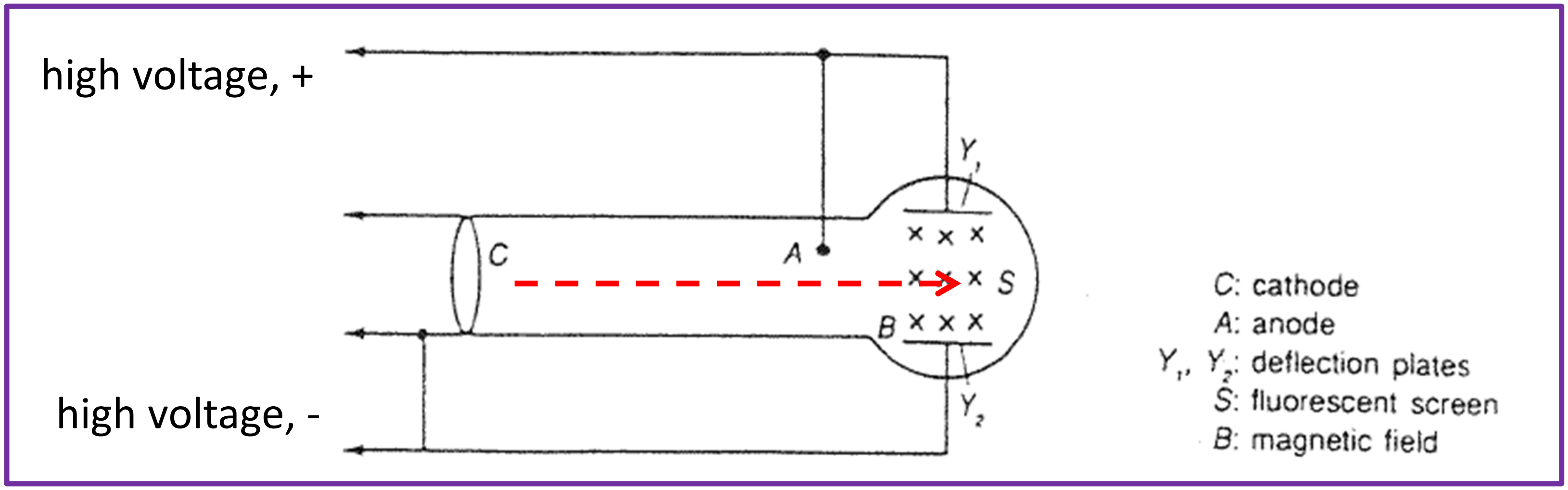
- ***Due to Electric & Magnetic Field. (E & B – field perpendicular)***
- **Path B : $F_E = F_B$ → qE = Bqv → ν = E/B**
- **Path A : $F_E > F_B$ → qE > Bqv → v < E/B ; v < ν**
- **Path C : $F_E < F_B$ → qE < Bqv → v > E/B ; v > ν**

Determination of specific charge of an electron



- The electron gun heats the cathode. The positive charged anode attracts the electrons from the negative cathode, and they pass through the anode to form a narrow beam in the space beyond.
- With E and B both zero, note the position of the spot on the screen.
- Using a fixed value of B alone, the beam is deflected downwards.
- The E field is adjusted until the spot returns to its initial undeflected position.

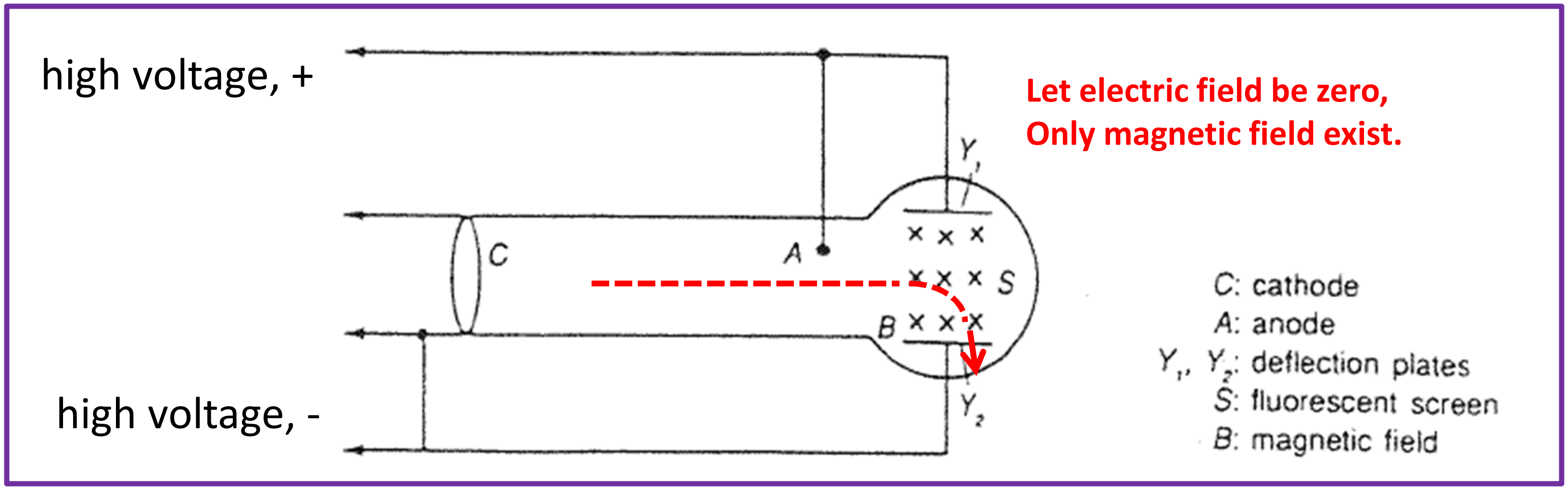
Determination of specific charge of an electron



<u>Method 1 of writing the equation **(for undeflected charge):**</u>

- At undeflected position, $F_E = F_B$; $v = E / B$
- Electron is emitted from cathode with zero speed, and through anode, then:
- $\frac{1}{2} mv^2 = qV$; subsitituting v = E / B
- $\frac{1}{2} m(E / B)^2 = qV$
- $q / m = E^2/2B^2V$; normally we use "e" to represent electron rather than q.
- $e / m = E^2/2B^2V$

Determination of specific charge of an electron



<u>Method 2 of writing the equation **(for deflected charge):**</u>

- **$\frac{1}{2} mv^2 = qV$**
- **$Bqv = mv^2 / r$** ; since magnetic force provides the centripetal force.
- **$v = Bqr / m$**
- **$\frac{1}{2} m(Bqr / m)^2 = qV$**
- **$q / m = 2V / B^2r^2$** ; substitute "e" to represent electron rather than q.
- **$e / m = 2V / B^2r^2$**

- Note: It is found that the specific charge of electron, e/m is to be $(1.758803 \pm 0.000003) \times 10^{11}$ Ckg^{-1}

Example 1

- An electron is travelling at right angles to a uniform magnetic field of flux density 1.2 mT. The speed of the electron is 8.0 x 10^6 ms^{-1}. Calculate the radius of circle describe by this electron.

- Predict the effect on the size and shape of the path that would be produced (separately) by each of the following changes.

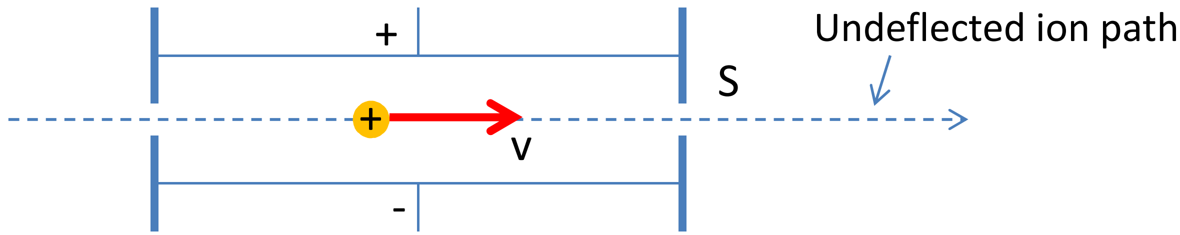
  a.) increasing the magnitude of flux density.

  b.) reversing the direction of the magnetic field.

  c.) slow down the electrons.

Example 2

- Balancing the effect of magnetic and electric fields is used in a device called velocity selector. This is use in devices such as mass spectrometers where it desired to produce a beam of charged particles all moving with the same velocity.



- Based on diagram above,

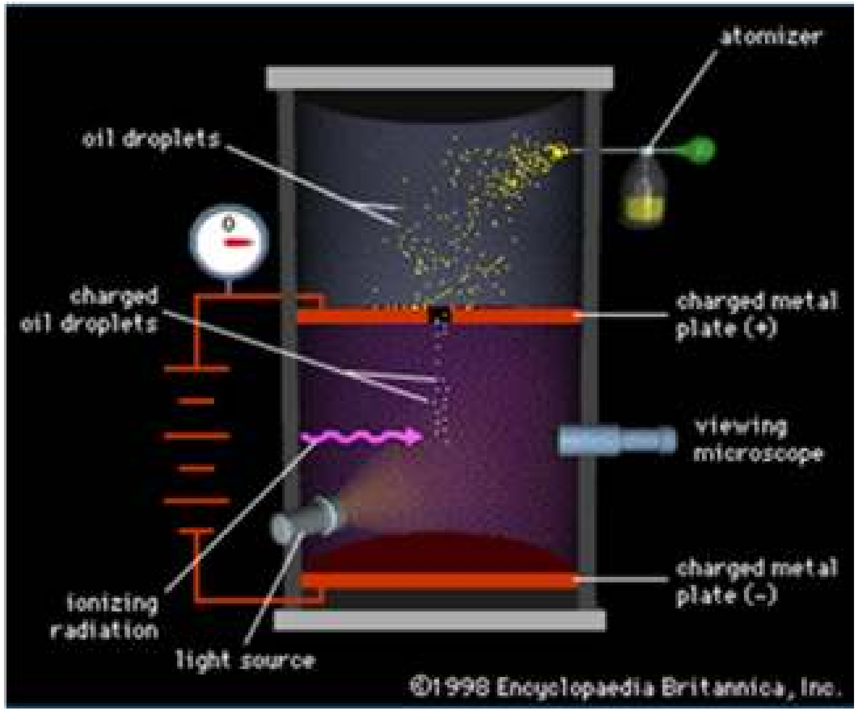
a.) state the directions of magnetic and electric forces on a positively charged ion travelling towards the slit S.

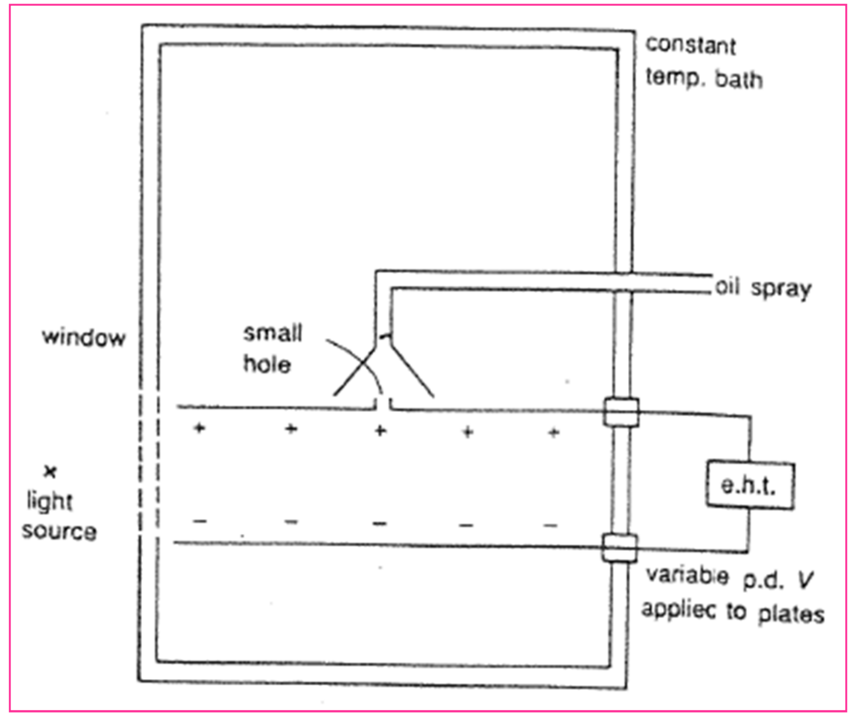
b.) What is the speed of the ions when the magnetic flux density is 0.30 T and electric field strength is 1.5×10^3 Vm^{-1}.

c.) Explain why ions travelling at speed greater than your answer in (b) will not emerge from the slit.

Principle of a method to measure the electron charge

Milikan's Oil Drop Experiment (Experiment Setup)





This method involves the balancing of the gravitational force of a tiny charged sphere by an electric force in the opposite direction so that the sphere remains stationary.

Principle of a method to measure the electron charge

Milikan’s Oil Drop Experiment

- The charge e of an electron is very small (-1.6×10^{-19} C) and difficult to measure.
- However, Robert Milikan, (American Scientist) devised an ingenious way to do it, publishing his results in 1913.He used tiny, charged droplets of oil 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.

$$\mathbf{mg = qV / d}$$

Principle of a method to measure the electron charge

Milikan’s Oil Drop Experiment

- Milikan’s procedure can be summed up as follows:
- He used an atomizer spray to produce a small number of tiny oil drops in the chamber. These drops were charged by friction with the nozzle of the spray.
- This tiny oil droplet is difficult to see unless strongly illuminated and viewed through a microscope.
- A large oil drop cannot be used because its weight will be much greater than any possible upward electrical force on the elementary charge.
- With the electric field switched off, he observed a single drop falling. If its velocity was constant, he knew that it was falling at terminal velocity.
- Thus, by timing its fall against a scale, he could determine its velocity, and from this he could work out the radius and the mass. (heavier drop falls with greater terminal velocity)

Principle of a method to measure the electron charge

Milikan's Oil Drop Experiment

- By applying Stoke's Law, Milikan was able to find the radius of the oil drop.

$r = \sqrt{(9\eta v / 2\rho g)}$; where r = radius of oil drop
v = terminal velocity
ρ = density of oil drop
g = acceleration of free fall
η = viscosity of air.

*Not in the syllabus

- He then switched on the electric field and adjusted it until the drop's weight was balanced by the electric force on it. ($mg = qV / d$)
- Milikan then alter the amount of charge on the oil drop by including a source of beta radiation in his apparatus. Each time a new charge in obtain, the p.d. is then change until the charge becomes stationary.
- Milikan repeated this step to many oil drops (a tricky procedure) and found that they were all small multiples of a particular value, which he took to be the charge of a single electron, e.

Quantisation of Charge

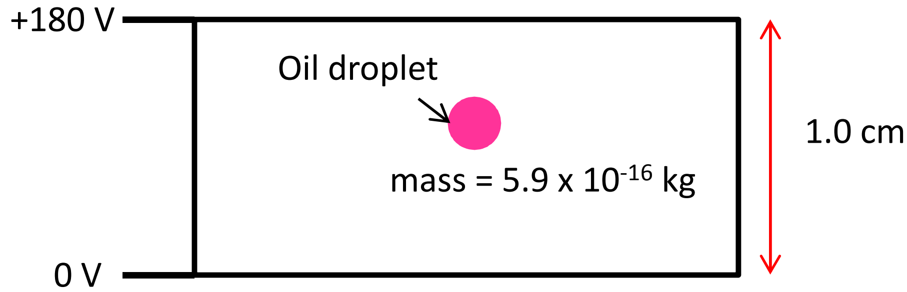
- The Milikan experiment was repeated many times to show what is meant by the term quantisation of charge.
- Typical results from the readings with a few droplets are shown in the table below.
- As can be observed, the charge on the droplet is not constant, but frequently around 1.6 x 10^{-19} C.
- When it does not have this value, it is either twice or thrice the value.

V /V	t /s	r /10^{-7} m	q /10^{-19} C
288	60.0	6.29	1.54
140	65.2	6.03	1.64
200	73.6	5.68	1.64
120	109.2	4.66	1.51
265	38.4	7.86	3.28
210	70.0	5.82	1.68
336	51.2	6.81	1.68
370	50.4	6.86	1.56
273	60.0	6.29	1.63
48	92.0	5.08	4.88
285	37.6	7.94	3.14
212	71.3	5.77	1.62

Quantisation of Charge

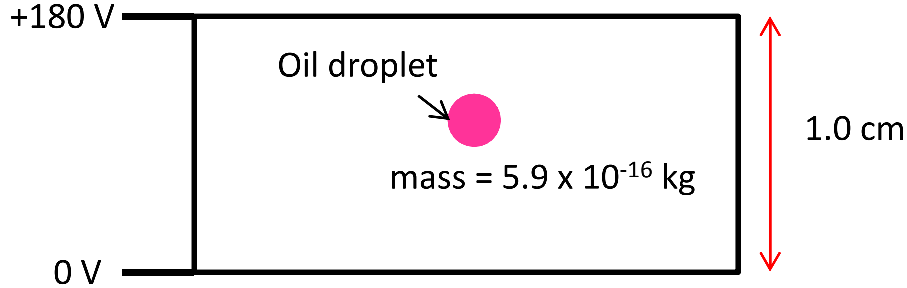
- Mililkan's value of e was within 1% of today's known value. The fact that his oil drops all had charges equal to the multiple of this value suggested that it was something very fundamental.
- It suggested that the electric charge is quantised, that is to say, that charge cannot take any value, rather, it must have a value which is a multiple of this fundamental value, e.
- We know that particles such as protons and many others from the "particles zoo" of sub-atomic particles have charges which are multiples of e.
- The exception thus far, is quarks, which have charges which are multiples of 1/3 e.

Example 3



- What is the sign of the charge on the droplet?
- What is the electric field strength between two plates?
- What is the weight of the droplet?
- What is the electric force acting on it when it is stationary?

Example 3 Cont…



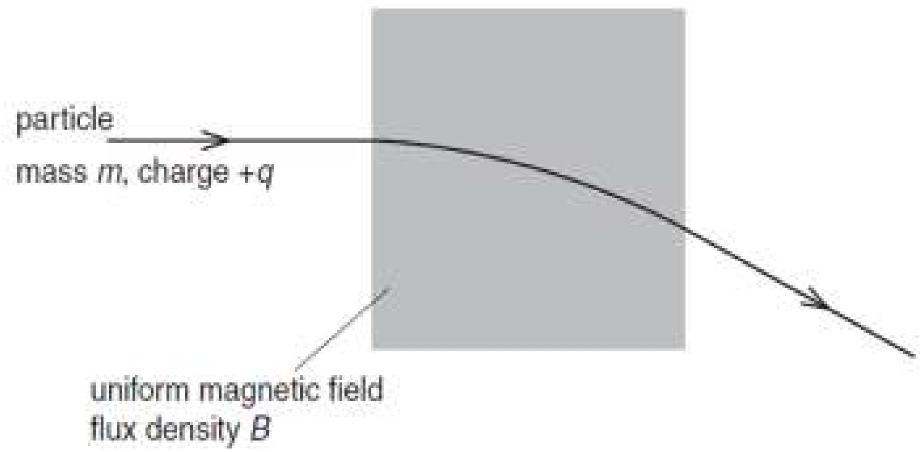
- What is the charge on the droplet?

- Beta radiation is included in the oil droplet and re-spray, the droplet was suddenly observed to start moving upwards. What explanation can you give for this?

- 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 you now expect in order to hold it stationary?

Example 4

- A charged particle of mass *m* and charge +*q* is travelling with velocity *v* in a vacuum. It enters a region of uniform magnetic field of flux density *B* as shown beside..



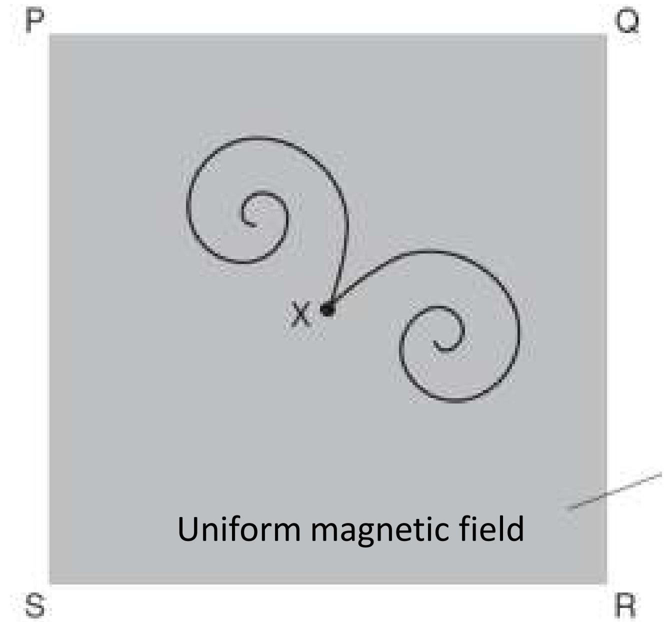
- The magnetic field is normal to the direction of motion of the particle. The path of the particle in the field is the arc of a circle of radius *r*.

(i) Explain why the path of the particle in the field is the arc of a circle.

(ii) Two parallel plates are placed horizontally (top and bottom) between the magnetic field in order to allow the charged particle to travel in a straight line. What should be the polarity of the top plate and why?

Example 5

- A uniform magnetic field is produced in the region PQRS, as shown. The magnetic field is normal to the page. At point X, a gamma-ray photon interaction causes two particles to be formed. The paths of these particles are shown on the right.



(i) Suggest, with a reason, why each of the paths is a spiral, rather than the arc of a circle.

(ii) State and explain what can be deduced from the paths about

1. the charges on the two particles,

2. the initial speeds of the two particles.