Turning Points

Discovery of the Electron

Name: ____________________

Class: ____________________

Date: ____________________

Time: **245 minutes**

Marks: **169 marks**

Comments:

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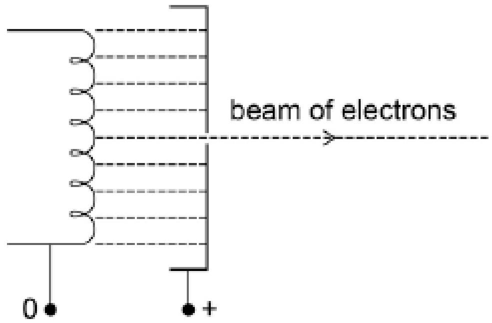
1 **Figure 1** shows a narrow beam of electrons produced by attracting the electrons emitted from a filament wire, to a positively charged metal plate which has a small hole in it.

Figure 1



(a) Explain why an electric current through the filament wire causes the wire to emit electrons.

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(2)

(b) Explain why the filament wire and the metal plates must be in an evacuated tube.

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(1)

(c) The potential difference between the filament wire and the metal plate is 4800 V.

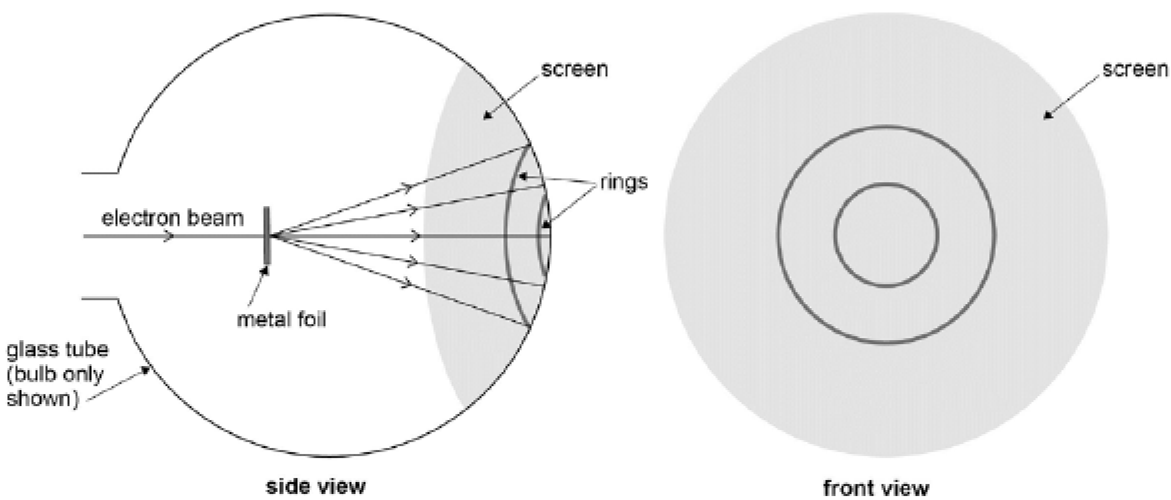
Calculate the de Broglie wavelength of the electrons in the beam.

wavelength = ____________________ m

(4)

The beam is directed at a thin metal foil between the metal plate and a fluorescent screen at the end of the tube, as shown in **Figure 2**.
The electrons that pass through the metal foil cause a pattern of concentric rings on the screen.

Figure 2



(d) The potential difference between the filament and the metal plate is increased. State and explain the effect this has on the diameter of the rings.

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(3)
(Total 10 marks)

2 (a) J J Thomson devised the first experiments to determine the specific charge for cathode rays produced in discharge tubes. He found that the value did not depend on the gas in the tube. He also discovered that particles emitted by a heated filament and particles emitted in the photoelectric effect had the same specific charge.

State **two** conclusions that were drawn from Thomson's experiments.

1. ____

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2. ____

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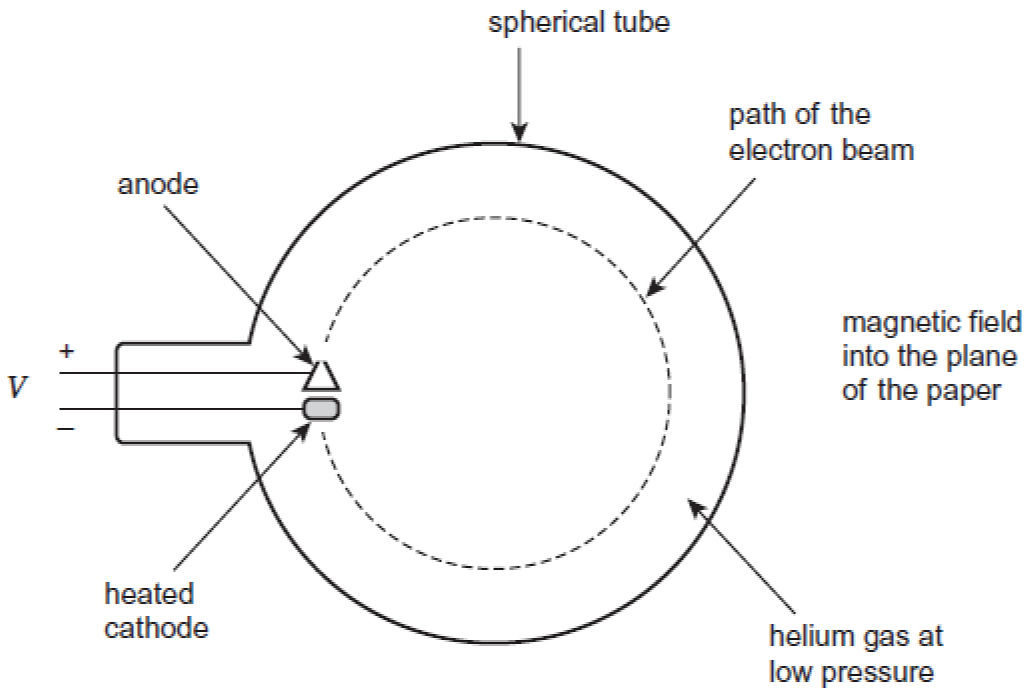
(2)

(b) The diagram shows a spherical tube, filled with low-pressure helium gas, that is used in an experiment to determine the specific charge of an electron.



Electrons are accelerated by a potential difference (pd) V applied between the cathode and anode. A magnetic field of known flux density B, directed into the plane of the diagram, causes the electrons to move in a circular path.

(i) Explain the process that causes the low-pressure helium gas to emit light so that the path of the electron beam can be seen.

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(3)

(ii) In one experiment using the apparatus in the diagram, the accelerating pd is 1.6 kV and the flux density of the magnetic field is 2.2 mT. The path of the electron beam has a radius of 0.059 m.

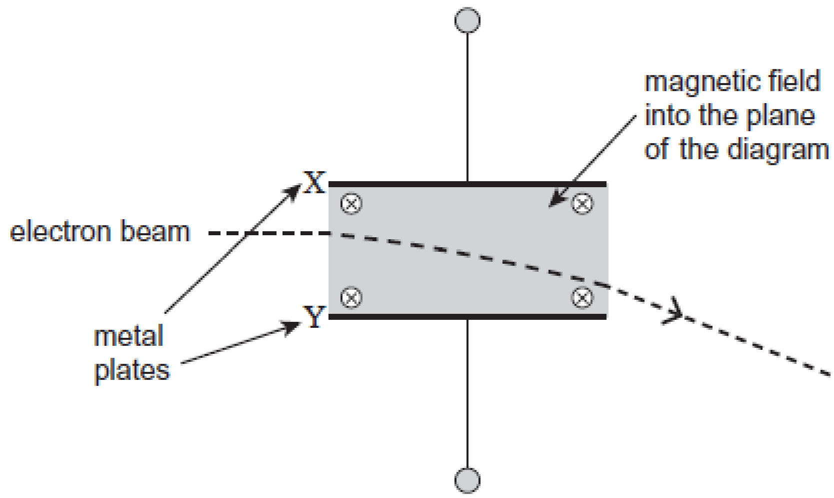
Determine a value for the specific charge of an electron using these data. State an appropriate unit for your answer.

specific charge = ____________________ unit = ____________

(4)

(Total 9 marks)

3 The diagram below shows part of an evacuated tube that is used to determine the specific charge (e / m) for an electron. An electron beam is directed between the two parallel metal plates, X and Y. In the region between the plates, a magnetic field is applied perpendicularly into the plane of the diagram. An electric field can be applied in this region by applying a potential difference (pd) between the plates.



(a) The diagram shows the path of the electron beam when the magnetic field is applied and the pd between X and Y is zero.

(i) Explain why the path followed by the electron beam in the magnetic field is a circular arc.

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(2)

(ii) Show that the speed v of the electrons is given by $v = \frac{Ber}{m}$

where r is the radius of the path of an electron in the magnetic field and B is the flux density of the magnetic field.

(1)

(iii) A pd V is now applied between X and Y without changing the flux density of the magnetic field. V is adjusted until the electron beam is not deflected as it travels in the region between the plates.

Determine an expression for the speed v of the electrons in terms of V, B and the separation d of the metal plates.

(1)

(b) Use the equation given in part (ii) and your answer to part (iii) to show that the specific charge for the electron = $\frac{V}{B^2 r d}$

(1)

(c) If the charge on an electron is known then its mass can be determined from the specific charge. Describe how Millikan's experiment with charged oil droplets enables the electronic charge to be determined.

Include in your answer:

- the procedures used to determine the radius of a droplet and the charge on a droplet
- how the measurements made are used
- how the electronic charge can be deduced.

The quality of your written communication will be assessed in your answer.

(6)
(Total 11 marks)

4 A charged oil droplet was observed falling between two oppositely charged parallel plates, as shown in **Figure 1.**

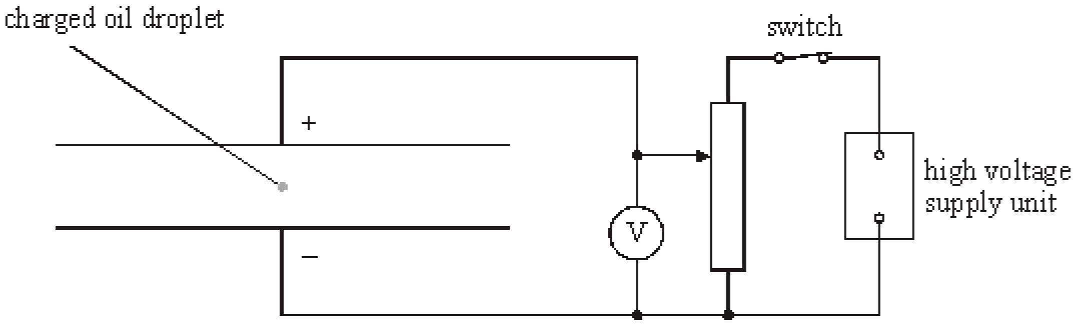

Figure 1

(a) Explain why the droplet stopped moving and remained stationary when the potential difference between the plates was adjusted to a certain value, V_c.

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(3)

(b) (i) The spacing between the plates is 6.0 mm. A charged oil droplet of mass 6.2×10^{-14} kg is stopped when V_c = 5700 V. Calculate the charge on this droplet.

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(ii) Describe and explain what would have happened to this droplet if the potential difference had been greater than 5700 V.

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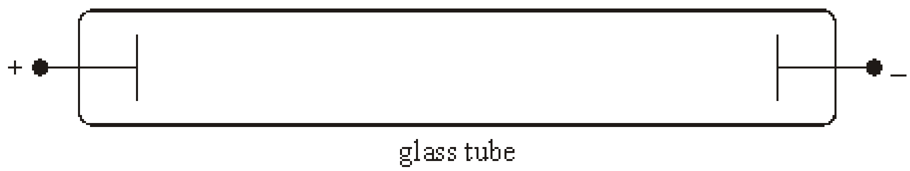
(5)

(Total 8 marks)

5 A potential difference was applied between two electrodes in a glass tube containing air, as shown in the diagram below. The pressure of the air in the tube was gradually reduced until a glow of light was observed between the electrodes.



(i) Explain why light was emitted.

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(ii) State why the glow was not observed until the pressure of the air in the tube was low enough.

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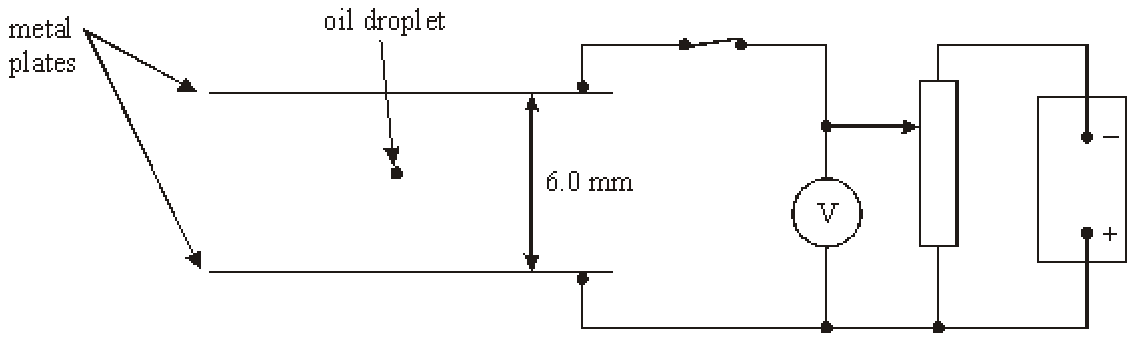
(Total 4 marks)

6

In an experiment to measure the charge on a charged oil droplet, a droplet was observed between two horizontal metal plates, as shown in the diagram below, spaced 6.0 mm apart.



(a) The oil droplet was held stationary when a negative potential of 320 V was applied to the top plate, keeping the lower plate at zero potential.

(i) State the sign of the charge on the droplet.

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(ii) With reference to the forces acting on the droplet explain why it was stationary.

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(2)

(b) The potential difference between the plates was then switched off and the droplet fell at constant speed through a vertical distance of 1.20 mm in 13.8 s.

(i) Calculate its speed of descent.

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(ii) By considering the forces on the spherical droplet of radius *r* as it falls at constant speed *v*, show that

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

where η is the viscosity of the air between the plates and ρ is the density of the oil. Ignore buoyancy effects.

(iii) Calculate the radius of the droplet and hence show that its mass is 2.6×10^{-15} kg.

viscosity of the air = 1.8×10^{-5} N s m^{-2}
density of the oil = 960 kg m^{-3}

(iv) Calculate the charge carried by this droplet.

(10)

(Total 12 marks)

7 Electrons are emitted by the process of *thermionic emission* from a metal wire in an *evacuated* container. The electrons are attracted to a metal anode which has a small hole at its centre. The anode is at a fixed *positive potential* relative to the wire. A beam of electrons emerges through the hole at constant velocity.

(a) Explain

(i) what is meant by thermionic emission,

(ii) why it is essential that the container is evacuated,

(iii) why the anode must be at a positive potential.

(4)

(b) An electron is accelerated from rest through a potential difference of 2500 V between the wire and the anode.

Calculate

(i) the kinetic energy of the electron at the anode,

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(ii) the speed of the electron at the anode. Ignore relativistic effects.

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(4)

(Total 8 marks)

8 In an experiment to measure the charge of an oil droplet, a positively charged oil droplet was held stationary by means of a uniform electric field of strength 4.9×10^5 V m^{-1}.

(a) (i) What was the direction of the electric field?

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(ii) Show that the specific charge of the oil droplet was 2.0×10^{-5} C kg^{-1}.

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(3)

(b) When the electric field was switched off the oil droplet fell and quickly reached constant speed.
Explain why the oil droplet reached constant speed.

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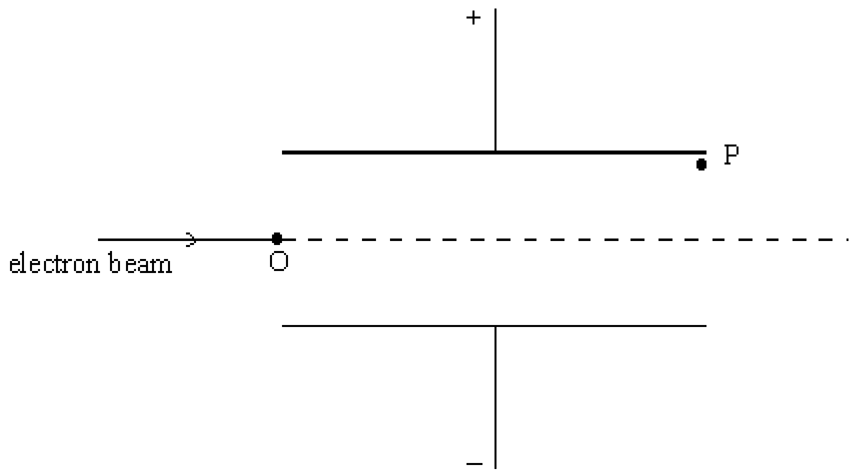
(3)

(Total 6 marks)

9 The diagram shows a narrow beam of electrons directed at right angles into a uniform electric field between two oppositely-charged parallel metal plates at a fixed potential difference.



(a) The electrons enter the field at O and leave it at P. Sketch the path of the beam from O to P and beyond P.

(2)

(b) A uniform magnetic field is applied to the beam perpendicular to the electric field and to the direction of the beam. The magnetic field reduces the deflection of the beam from its initial direction.

(i) Explain why the magnetic field has this effect on the beam.

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(ii) The magnetic flux density is adjusted until the beam passes through the two fields without deflection. Show that the speed $\boldsymbol{v}$ of the electrons when this occurs is given by

$$v = \frac{E}{B}$$

where E is the electric field strength and B is the magnetic flux density.

(5)

(c) In an experiment to measure the specific charge of the electron, electrons were accelerated from rest through a potential difference of 2900 V to a speed of 3.2×10^7 m s^{-1}. Use this information to calculate the specific charge of the electron.

(3)

(Total 10 marks)

10 **Figure 1** shows an electron gun that produces electrons with a kinetic energy of 6.0×10^{-16} J.

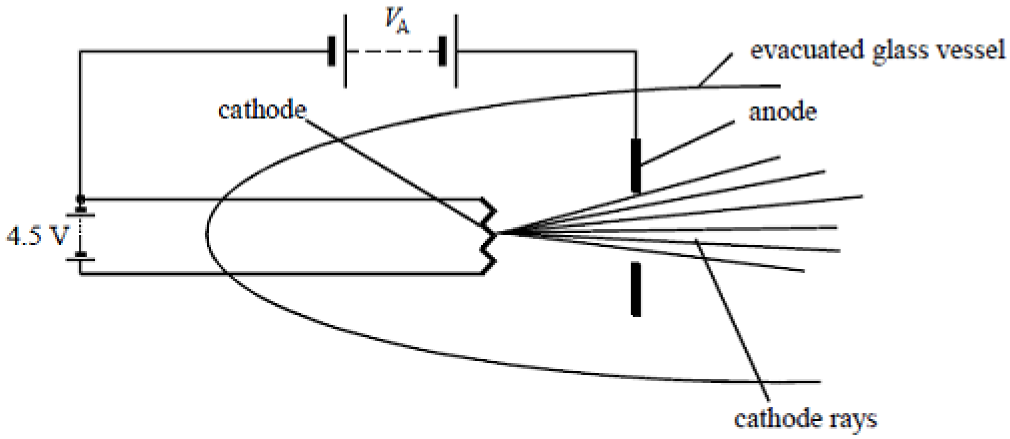

Figure 1

(a) (i) Calculate the cathode-anode potential, V_A.

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(ii) What part does the 4.5 V power supply play in producing electrons?

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(4)

(b) After leaving an electron gun, a narrow beam of electrons of speed 3.6×10^7 m s^{-1} enters a uniform electric field at right angles to the field. The electric field is due to two oppositely charged parallel plates of length 60 mm, separated by a distance of 25 mm as shown in **Figure 2**. The potential difference between the plates is adjusted to 1250 V so that the beam just emerges from the field at P without touching the positive plate.

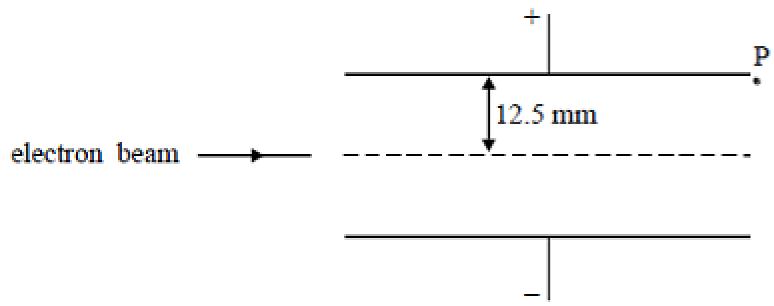

Figure 2

(i) On **Figure 2**, sketch the path of the beam in the field and beyond.

(ii) Calculate the time for which each electron is between the plates.

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(iii) Use the data above to calculate the specific charge of the electron, e/m.

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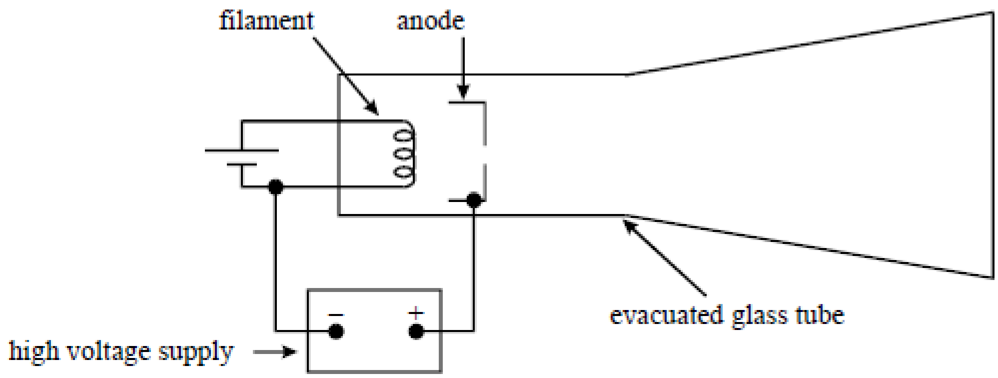
(8)

(Total 12 marks)

11 (a) A beam of monoenergetic electrons is produced by *thermionic emission* from a metal filament, using an arrangement represented in the diagram.



(i) Describe the process of thermionic emission.

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(ii) Explain why thermionic emission is negligible when the filament current is too low.

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(4)

(b) The anode is at a positive potential of 4200 V with respect to the filament.

(i) Calculate the kinetic energy, in J, of an electron in the beam in part (a) as it passes through the anode.

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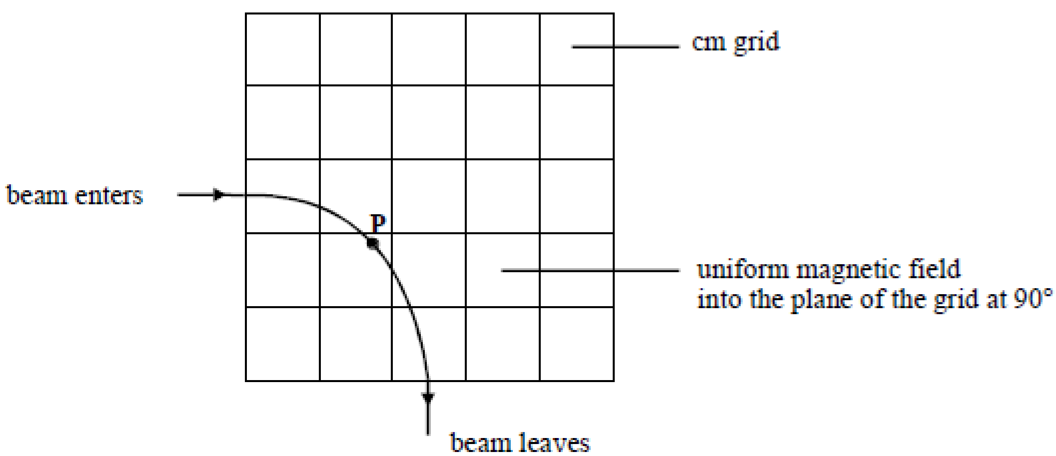
(ii) Calculate the speed of the electrons in this beam as they pass through the anode. Ignore relativistic effects.

(4)

(Total 8 marks)

12 (a) An electron beam enters a uniform magnetic field and leaves at right angles, as shown in the diagram which is drawn to full-scale.



(i) Draw an arrow at P to show the direction of the force on an electron in the beam.

(ii) Explain why the kinetic energy of the electrons in the beam is constant.

(3)

(b) (i) Measure the radius of curvature of the electron beam in the diagram

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(ii) The electron beam was produced by means of an electron gun in which each electron was accelerated through a potential difference of 3.2 kV. The magnetic flux density was 7.6 mT. Use these data and your measured value of the radius of curvature of the electron beam to determine the specific charge of the electron, e/m.

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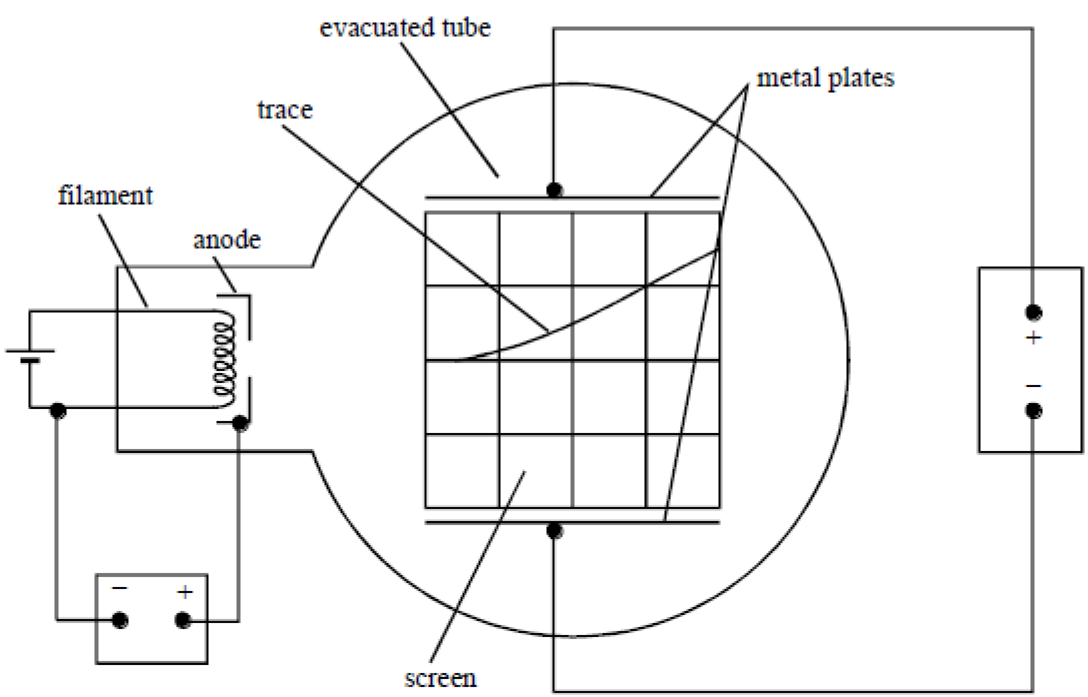
(6)

(Total 9 marks)

13 A narrow beam of electrons is directed into a uniform electric field created by two oppositely-charged parallel metal plates at right angles to the field lines. A fluorescent screen is used to make the beam give a visible trace.



(a) (i) Explain why the beam curves towards the positive plate.

(ii) How does the trace show that, on entry to the electric field, all the electrons have the same speed?

(3)

(b) The beam is produced as a result of accelerating electrons between the filament and a metal anode.

(i) Explain why the wire filament must be hot.

(ii) Write down an equation relating the speed of the electrons, v, to the potential difference, V_A, between the anode and the filament.

(2)

(c) The deflection of the beam due to the electric field can be cancelled by applying a suitable uniform magnetic field *in* the same region as the electric field.

(i) What direction should the magnetic field be in to do this?

(ii) Write down an equation relating the speed of the electrons v to the plate voltage V_p, the plate separation d, and the magnetic flux density B necessary to make the beam pass undeflected between the plates.

(iii) The following measurements were made when the beam was undeflected.

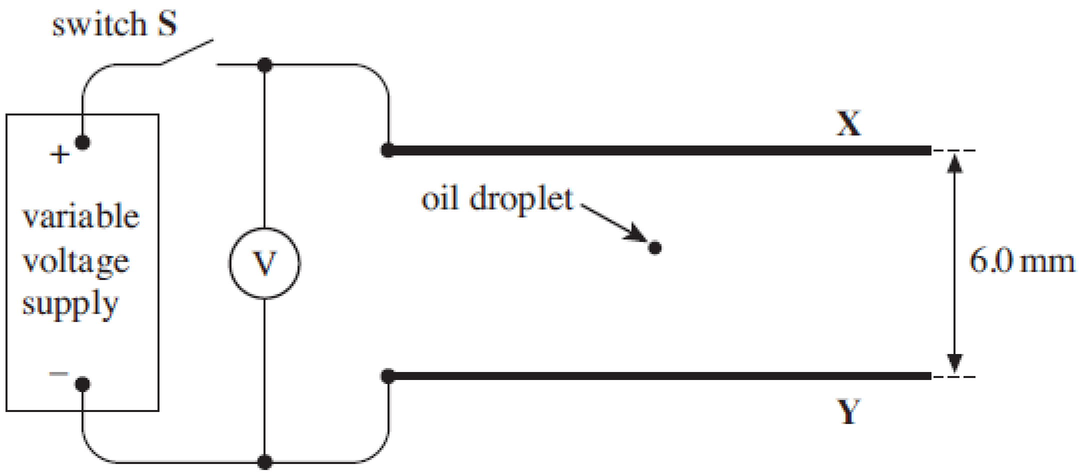
V_A = 3700 V V_p = 4500 V d = 50 mm B = 2.5 mT

Use the two equations you have written down and the given data to calculate the specific charge, e/m, of the electron.

(5)

(Total 10 marks)

14 A charged oil droplet was observed between two horizontal metal plates **X** and **Y**, as shown in the diagram below.



(a) (i) With the switch **S** open, the droplet fell vertically at a constant velocity of 1.1×10^{-4} ms^{-1}. Show that the radius of the droplet is about 1.0×10^{-6} m. Assume the droplet is spherical.

density of oil, $\rho = 880$ kg m^{-3}
viscosity of air, $\eta = 1.8 \times 10^{-5}$ N s m^{-2}

(4)

(ii) Calculate the mass of the droplet.

mass ____________________ kg

(1)

(iii) The switch **S** was closed and the potential difference from the voltage supply was adjusted gradually to reduce the downward motion of the droplet. The droplet stopped moving when the potential difference across the plates was 680 V. The spacing between the plates was 6.0 mm.

Calculate the magnitude of the charge on the droplet.

charge ____________________ C

(3)

(b) The mass of another charged droplet was found to be 4.3×10^{-15} kg. With switch **S** closed and the voltage supply at its maximum value of 1000 V, this droplet fell more slowly than when the switch was open but it could not be stopped.

Explain why this droplet could not be held at rest and show that the magnitude of the charge on it was 1.6×10^{-19} C.

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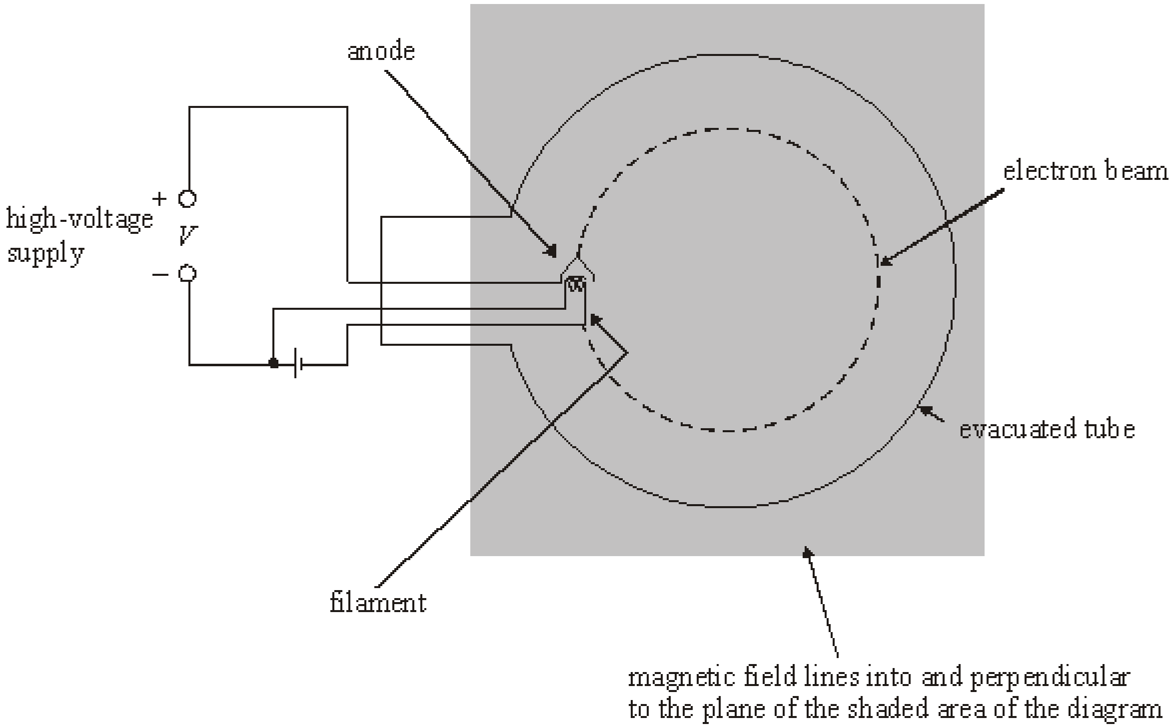
(4)

(Total 12 marks)

15 The figure below shows an electron gun in an evacuated tube. Electrons emitted by *thermionic emission* from the metal filament are attracted to the metal anode which is at a fixed potential, *V*, relative to the filament. Some of the electrons pass though a small hole in the anode to form a beam which is directed into a uniform magnetic field.



(a) (i) Explain what is meant by thermionic emission.

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(ii) Show that the speed, v, of the electrons in the beam is given by

$$v = \left(\frac{2eV}{m}\right)^{\frac{1}{2}}$$

where *m* is the mass of the electron and *e* is the charge of the electron.

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(3)

(b) The beam of electrons travels through the field in a circular path at constant speed.

(i) Explain why the electrons travel at constant speed in the magnetic field.

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(ii) Show that the radius, *r*, of the circular path of the beam in the field is given by

$$r = \left(\frac{2mV}{B^2 e}\right)^{\frac{1}{2}}$$

where *B* is the magnetic flux density and *V* is the pd between the anode and the filament.

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(iii) The arrangement described above was used to measure the specific charge of the electron, *e/m*. Use the following data to calculate *e/m*.

B = 3.1 mT
r = 25 mm
V = 530 V

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(7)
(Total 10 marks)

16 A narrow beam of electrons is produced in a vacuum tube using the arrangement shown in **Figure 1.**

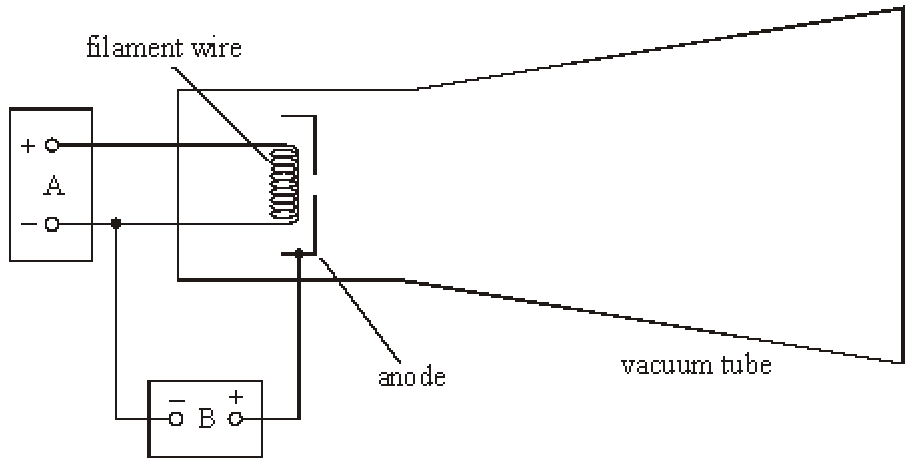

Figure 1

(a) Describe the function of each voltage supply unit and state a typical voltage for each unit.

(i) unit A

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___

(ii) unit B

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(3)

(b) State and explain the effect on the beam of

(i) reducing the voltage of A,

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(ii) increasing the voltage of B.

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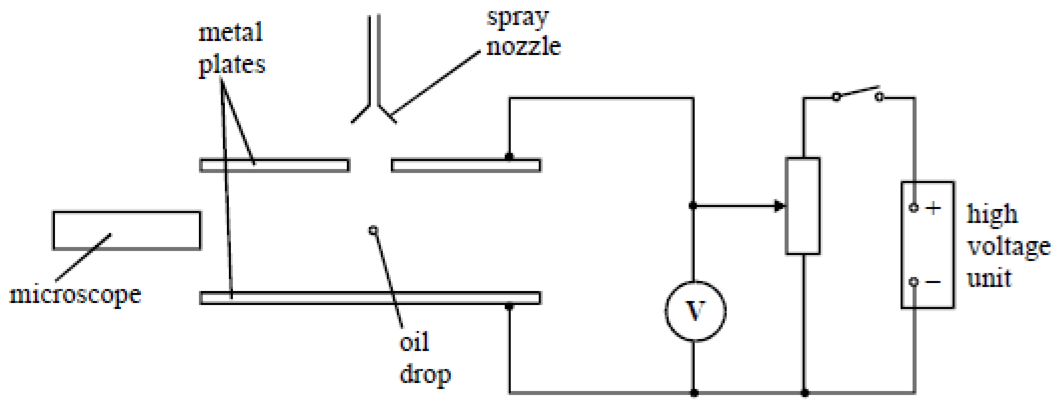
(4)
(Total 7 marks)

17 Millikan determined the charge on individual oil droplets using an arrangement as represented in the diagram. The plate voltage necessary to hold a charged droplet stationary was measured. The time the droplet took to fall a known distance with the plate voltage off was then measured.



(a) (i) Explain why a charged oil droplet reaches a constant speed when the plate voltage is switched off.

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(ii) By considering the forces on such a droplet, show that the radius, r, of the droplet is related to the speed, υ by

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

where η is the viscosity of air and ρ is the density of the oil. Ignore the effects of buoyancy.

(6)

(b) In an experiment to measure the charge on an oil droplet, a charged droplet was held stationary by a voltage of 225 V between two plates at a separation of 5.0 mm. When the plate voltage was switched off, the droplet descended a vertical distance of 1.20 mm in a time of 15.5 s.
Ignore the effect of buoyancy of the air.

density of oil = 950 kg m^{-3}
viscosity of air = 1.8×10^{-5} N s m^{-2}

(i) Show that the mass of this droplet was 2.2×10^{-15} kg.

(ii) Calculate the charge carried by this droplet.

(6)

(c) Millikan measured the charge on each of many oil droplets. Explain what he concluded from his measurements.

(2)

(Total 14 marks)

18 (a) In a cathode ray tube, electrons emitted from a cathode are attracted towards an anode by means of a large potential difference. If the anode-cathode potential difference is 2200 V, calculate the kinetic energy, in J, and speed of each electron just before impact at the anode.

(2)

(b) (i) If an electron of this energy was to impinge on a fluorescent screen, calculate the shortest wavelength of the electromagnetic radiation subsequently emitted and explain why this is a minimum value.

(ii) Calculate the de Broglie wavelength of an electron with the same energy as that hitting the screen previously.

(7)

(Total 9 marks)

Mark schemes

1 (a) current heats the wire ✓ **1**

electrons (in filament) gain sufficient KE (to leave the filament) ✓ **1**

(b) electrons would collide (or be absorbed or scattered) by gas atoms (or molecules) ✓ **1**

(c) Rearrange ½ $m v^2 = eV$ to give $v = (2eV/m)^{1/2}$ **1**

or correct substitution in equation. **1**

$$v = \left(\frac{2 \times 1.6 \times 10^{-19} \times 4800}{9.1 \times 10^{-31}}\right)^{½} = 4.1 \times 10^{7}\ \text{m s}^{-1}$$ **1**

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 4.1 \times 10^{7}}\ ✓ = 1.8 \times 10^{-11}\ \text{m}\ ✓$$ **1**

(d) Increasing the pd increases the speed (or kinetic energy or momentum) of the electrons ✓ **1**

which decreases their de Broglie wavelength ✓ **1**

so they are diffracted less so the rings become smaller ✓ **1**

[10]

2 (a) Experiments suggested cathode rays were negatively charged particles ✓

Particle has mass much smaller than mass of an atom / hydrogen ion
OR
Compares Specific charge with that of hydrogen ion / atom ✓

Particles were part of the substructure of matter / atoms ✓

Particles emitted in each case were the same
OR
Particles emitted were the same for different gases / for photoelectrons and particles from thermionic emission ✓

MAX 2

Specific charge defined =0

Millikan / Rutherford deductions=0

Do not allow small mass alone

Allow proton

Allow two correct deductions in 1 or 2 provided that the other comment is not relevant but does not contradict,

2

(b) (i) electrons collide with atoms of gas ✓ (condone molecules)

Reference to collisions with nucleus = 0 for the question

atoms / electrons are excited

or atoms / electrons change to higher energy states ✓

light / photon emitted when relaxation / de-excitation occurs or as electrons move / fall back to lower energy level ✓

Do not allow

- *collide with gas unless atoms mentioned later*
- *particles*
- *electrons absorbed by atoms*

Allow move from ground state

Allow return to ground state

3

(ii) $eV = \frac{1}{2} mv^2$ and $\frac{mv^2}{r} = Bev$ or $\frac{e}{m} = \frac{v}{Br}$ in any form ✓
or $\frac{e}{m} = \frac{2V}{B^2 r^2}$

Correct substitution of data in the question allowing errors in powers of 10 ✓

1.9×10^{11} ✓

C kg^{-1} ✓

Do not allow

Must be seen

Substitution of values of e and m_e can gain 1st and last marks only

4

[9]

3 (a) (i) There is a (constant) force acting which is (always) at right angles / perpendicular to the path / motion / velocity / direction of travel / to the beam
Or mentions a centripetal force ✓

First mark is for condition for circular motion

Not speed

Second mark is for a statement relating to the origin of the force

Force is at right angles to the magnetic field and the electron motion
Or
direction given by left hand rule ✓

Any mention of attraction to the plates is talk out (TO)

2

(ii) States $Bev = \frac{mv^2}{r}$ and evidence of correct intermediate stage showing manipulation of the formula
or

Quotes $r = \frac{mv}{Be}$ from formula sheet and change of subject to $v = Ber / m$ seen

Accept delete marks

or rewrite as $Be = \frac{mv}{r}$

or rearrangement as $\frac{v^2}{v} = \frac{Ber}{m}$

1

(iii) States $Bev = \frac{eV}{d}$

or $F = Bev$ $F = \frac{eV}{d}$ (or $F=Ee$ *and* $E = \frac{V}{d}$ in any form)

Allow use of e or Q

<u>and</u>

states $v = \frac{V}{Bd}$ ✓

No mark for just quoting final equation. There must be evidence of useful starting equations

1

(b) Equates the formulae for *v* and shows $\frac{e}{m}$ equated to $\frac{V}{B^2rd}$

Must include 'e / m =' not just 'specific charge ='

Note there is no ecf. Candidates who use an incorrect equation in (a) (iii) will lose this mark unless they restart from first principles

Condone Q / m

1

(c) Using band marking

Marks awarded for this answer will be determined by the Quality of Written Communication (QWC) as well as the standard of the scientific response.
Level 1 (1−2 marks)
Answer is largely incomplete. It may contain valid points which are not clearly linked to an argument structure. Unstructured answer. Errors in the use of technical terms, spelling, punctuation and grammar or lack of fluency.
Level 2 (3−4 marks)
Answer has some omissions but is generally supported by some of the relevant points below: - the argument shows some attempt at structure - the ideas are expressed with reasonable clarity but with a few errors in the use of technical terms, spelling, punctuation and grammar.
Level 3 (5−6 marks)
Answer is full and detailed and is supported by an appropriate range of relevant points such as those given below: - argument is well structured with minimum repetition or irrelevant points - accurate and clear expression of ideas with only minor errors in the use of technical terms, spelling and punctuation and grammar.

A

Measure the terminal speed of the falling droplet

At the terminal speed weight = viscous force (+ upthrust)

$mg = 6\pi\eta rv$ and $m = 4\pi r^3\rho / 3$ so $r^2 = \frac{9\eta v}{2\rho g}$

r could be determined as density of drop, viscosity of air and *g* are known (*r* is the only unknown)

B

m can be determined if *r* is known

Apply pd between the plates so electric field = V / d and adjust until droplet is stationary

$QV / d = mg$ so *Q* can be found

C

Make a number of measurements to find *Q*

Results for *Q* are in multiples of 1.6×10^{-19}C so *Q* can be found

e.g.

1-2

Superficial with some sensible comments about the procedure with significant errors in attempts at use of equations. May do one part of A B or C reasonably well. Relevant Equations without little explanation may be worth 1

3-4

Should cover most of the point in two of A, B & C coherently

A & B may be well done in an answer that is easy to follow

OR B and C may be well explained but there may be significant errors or omissions in the determination of r

OR a bit of all A B and C with significant errors or omissions

5-6

Will cover the points made in A B & C with few omissions in an answer that is easy to follow

The candidate will define some terms used in equations

1-2

Attempt to explain how to determine radius with detail of how to use data

OR

Makes a relevant point about some part of the procedure about the determination

3-4

Radius determination explained with sensible equations

Explanation of how to use data to find mass of the drop

Idea of holding the drop stationary

5-6

Answer includes all steps to determine the charge of a droplet with correct equations showing how to use the measurements

For highest mark the answer should include idea of interpreting results of many measurements

6

[11]

4 (a) force due to electric field is vertically upwards and proportional (or related to) plate pd **(1)**
at $V = V_c$, force due to field is equal and opposite to the weight of the droplet **(1)**
no resultant force (or forces balance) at V_c (droplet remains stationary) **(1)**

3

(b) (i) electric force (or qV/d) = weight (or mg) **(1)**

$$q\left(=\frac{mgd}{V}\right) = \frac{6.2\times10^{-14}\times9.8\times6.0\times10^{-3}}{5700}$$ **(1)**

$= 6.4 \times 10^{-19}$C **(1)**

(ii) for pd > 5700 (V), droplet moves upwards **(1)**
due to increased electric force **(1)**
droplet reaches terminal velocity **(1)**

max 5

[8]

5 (i) electrons [or ions] present **(1)**
electrons/ions accelerated by electric field
[or electrons and ions collide] **(1)**
excitation/ionisation of gas atoms/ions/molecules/particles occur **(1)**
photons emitted on return to lower energy or ground state **(1)**

(ii) electrons/ions do not gain enough kinetic energy (to produce ionisation) **(1)**
because too many atoms/ions/molecules/particles present **(1)**

max 4
QWC 1

[4]

6 (a) (i) positive **(1)**

(ii) electric force directed **upwards** = weight **(1)**
[or $\frac{QV}{d} = mg$]

2

(b) (i) $v = \frac{1.20\times10^{-3}}{13.8} = 8.7 \times 10^{-5}$ m s^{-1} **(1)**

(ii) weight [or mg] = $\frac{4}{3}\pi r^3 \rho g$ **(1)**
(since speed constant) viscous force = $6\pi\eta rv$ **(1)**
$\therefore \frac{4}{3}pr^3\, rg = 6\pi\eta rv$ to give desired equation **(1)**

(iii) rearrange equation to give $r = \left(\frac{9\eta v}{2\rho g}\right)^{1/2}$ **(1)**

$\left\{ = \left(\frac{9 \times 1.8 \times 8.7 \times 10^{-5}}{2 \times 960 \times 9.8}\right)^{1/2} \right\}$ = 8.7 × 10^{-7} m **(1)** **(**8.65 × 10^{-7} m)

(allow C.E. for value of *v* from (i), but not 3rd mark)
m (= $^4/_3\ \pi r^3\ \rho$) = $^4/_3\ \pi$ (8.65 × 10^{-7})^3 × 960 **(1)** (= 2.6 × 10^{-15} kg)

(iv) $\frac{QV}{d} = mg$ **(1)**

$Q = \frac{2.6 \times 10^{-15} \times 9.8 \times 6.0 \times 10^{-3}}{320}$ **(1)**

= 4.8 × 10^{-19} C **(1)** (4.78 × 10^{-19} C)

10

[12]

7 (a) (i) metal wire emits electrons when heated **(1)**
conduction electrons in metal gain kinetic energy when wire is heated **(1)**

(ii) electrons from wire would be absorbed/scattered/stopped by gas atoms
or collide with gas atoms and lose kinetic energy or speed **(1)**

(iii) electrons carry negative charge so anode needs to be positive (to attract them) **(1)**

4

(b) (i) E_k (or ½mv^2) (= work done or eV) = 1.6 × 10^{-19} × 2500 **(1)**
= 4.0 × 10^{-16} J **(1)**

(ii) $v\left(= \left(\frac{2E_k}{m}\right)^{1/2}\right) = \left(\frac{2 \times 4.0 \times 10^{-16}}{9.11 \times 10^{-31}}\right)^{1/2}$ **(1)**

= 3.0 × 10^7 m s^{-1} **(1)**

(allow C.E. for value of E_k from (i))

4

[8]

8 (a) (i) (vertically) upwards **(1)**

(ii) $mg = qE$, ∴ $\frac{q}{m} = \frac{g}{E}$ **(1)**

$\frac{9.8}{4.9 \times 10^5}$ (1) (= 2.0 × 10^{-5} C kg^{-1})

3

(b) initial downwards acceleration due to weight (or gravity) **(1)**
viscous force/drag/friction (or resistance) due to air
increases with increase in speed **(1)**
speed increases until drag become equal to (and opposite to) weight
(no resultant force) hence no acceleration **(1)**

max 3

[6]

9 (a) path curves upwards from O to P
path is tangential to curve at P and straight beyond P

2

(b) (i) magnetic field exerts a force on a moving charge/electron **(1)**
magnetic force has a downwards component (at all points)
[or magnetic force < electric force] **(1)**

(ii) magnetic force = *Bev* **(1)**

electric force $\left(\frac{eV_p}{d}\right)$ = *eE* **(1)**

Bev = *eE* (gives $v = \frac{E}{B}$) **(1)**

5

(c) work done (or *eV*) = gain of kinetic energy (or ½mv^2) **(1)**

$\frac{e}{m} = \frac{v^2}{2}$ **(1)**

$= \frac{(3.2 \times 10^7)^2}{2 \times 2900}$ = 1.8 × 10^{11} C kg^{-1} **(1)**

3

[10]

10 (a) (i) $V\left(= \frac{W}{Q}\right) = \frac{6.0 \times 10^{-16}}{1.60 \times 10^{-19}}$ **(1)** = 3750 V **(1)**

(ii) heats the filament [or cathode or wire] **(1)**
to enable electrons to gain (sufficient) k.e. to leave filament
[or cause thermionic emission] **(1)**

(4)

(b) (i) electron moves towards positive plate
curve in field **(1)**
and straight beyond **(1)**

(ii) $t\left(= \frac{l}{v} = \frac{0.060}{3.6 \times 10^7}\right)$ = 1.67 ns **(1)**

(iii) $y = -\frac{1}{2} at^2$ **(1)**

$a = \frac{eV_p}{md}$ **(1)**

combine to give $\frac{e}{m} = \frac{2yd}{V_p t^2}$ **(1) =** $\frac{2 \times 12.5 \times 10^{-3} \times 25 \times 10^{-3}}{1250 \times (1.67 \times 10^{-9})^2}$ **(1)**

$= 1.8 \times 10^{11}$ C kg^{-1} **(1)**

(max 8)

[12]

11 (a) (i) filament heated by an electric current
[or metal heated by nearby hot wire filament] **(1)**
(conduction) electrons in the metal gain sufficient
kinetic energy to leave the metal / cathode / filament **(1)**

(ii) temperature of filament depends on the current
or low current so small heating effect] **(1)**
kinetic energy of electrons depends on temperature of filament **(1)**
electrons must do work (or overcome work function) to leave metal **(1)**
electrons have insufficient (kinetic) energy to leave
metal / cathode / filament (or overcome work function)
if the current is too low **(1)**

4

(b) (i) E_k (= eV = 1.6 × 10^{-19} × 4200) = 6.7 × 10^{-16} (J) **(1)**

(ii) (use of $E_k = ½mv^2$ gives) $½mv^2$ = 6.7 × 10^{-16} (J) **(1)**
(allow C.E. for value of E_k)

$$v = \left(\frac{2 \times 6.7 \times 10^{-16}}{9.1 \times 10^{-31}}\right)^{1/2}$$ **(1)**

= 3.8 × 10^7 m s^{-1} **(1)**

4

[8]

12 (a) (i) arrow pointing towards centre of curvature **(1)**

(ii) velocity [or direction of motion] is perpendicular

to the direction of the force **(1)**

work done is force × distance moved in the direction of the force **(1)**

no work done as there is no motion in the direction of the force **(1)**

(max 3)

(b) 25mm **(1)**

$\frac{1}{2}mv^2 = eV$ **(1)**

$\frac{mv^2}{r} = Bev$ **(1)**

$\frac{e}{m} = \frac{2V}{B^2r^2}$ **(1)** $= \frac{2 \times 3200}{(7.6 \times 10^{-3})^2 \times 0.025^2}$ **(1)** $= 1.8 \times 10^{11}$ C kg^{-1} **(1)**

(6)

[9]

13 (a) (i) electrons are negatively charged so beam is attracted to positive plate [or repelled by negative plate or electron experiences force towards positive plate] **(1)**

(ii) beam does not spread out **(1)**
if speeds varied, faster electrons would be deflected less than slower electrons **(1)**

3

(b) (i) to give conduction electrons sufficient k.e. to leave metal [or to cause thermionic emission or electrons have insufficient ke. in a cold filament to leave filament] **(1)**

(ii) $\frac{1}{2}mv^2 = eV_A$ [or $v = \sqrt{\frac{2eV_A}{m}}$] **(1)**

2

(c) (i) into the plane of the diagram **(1)**
perpendicular to the diagram [or the electric field] **(1)**

(ii) $Bev = \frac{eV_P}{d}$ **(1)**

(iii) combine the two equations to give $\frac{e}{m} = \frac{V_P^2}{2V_AB^2d^2}$ **(1)**

$\frac{e}{m} = \frac{4500^2}{2 \times 3700 \times (2.5 \times 10^{-3})^2 \times (50 \times 10^{-3})^2}$ **(1)**

1.75×10^{11} Ckg^{-1} **(1)**

max 5

[10]

14 (a) (i) (at terminal velocity v), weight of droplet (or mg) = viscous drag (or $6\pi\eta r v$) ✓

Backward working 3 marks max;

viscous force (= $6\pi\eta r v$) = $6\pi \times 1.8 \times 10^{-5} \times 1.0 \times 10^{-6} \times 1.1 \times 10^{-4} = 3.7 \times 10^{-14}$ N ✓

mass (m) of droplet = ($4\pi r^3 / 3$) × ρ , (where r is the droplet radius) ✓

weight = mg =

$$\frac{4}{3}\pi(1.0 \times 1.0^{-6})^3 \times 880 \times 9.8 = 3.6 \times 10^{-14}\text{N}$$ ✓

(allow 3.7)

(therefore) ($4\pi r^3 / 3$) × $\rho g = 6\pi\eta r v$ (or rearranged) ✓

(hence) r (= $(9 \eta v / 2 \rho g)^{1/2}$

$$= \frac{9 \times 1.8 \times 10^{-5} \times 1.1 \times 10^{-4}}{2 \times 880 \times 9.8}) \text{ gives } r = 1.0(3) \times 10^{-6} \text{ m}$$ ✓

(therefore) viscous force = weight as required for constant velocity ✓

note; some evidence of calculation needed to give final mark

Allow final answer for r in the range 1 to 1.05 × 10^{-6} to any number of sig figs

4

(ii) $\boldsymbol{m} = ((4\pi r^3/3) \times \rho) = \frac{4}{3}\pi(1.0 \times 10^{-6})^3 \times 880) = 3.7 \times 10^{-15}$ kg ✓

Allow ecf for r from a(i) in a correct calculation that gives m in the range 3.6 to 4.0 × 10^{-15} kg

(or correct calculation of $6\pi\eta r v / g$)

1

(iii) electric force (or QV / d) = droplet weight (or *mg*) ✓

Allow ecf m (or r) from a(ii) (or a(i)).

$$Q = \left(\frac{mgd}{V} \right) = \frac{3.7\times10^{-15}\times9.8\times6.0\times10^{-3}}{680}\ ✓$$

Accept values in 1st mark line

[or Q (= viscous force × *d / V*

Use of e instead of Q or q = 2 marks max

$= 6\pi \times 1.8 \times 10^{-5} \times 1.0 \times 10^{-6} \times 1.1 \times 10^{-4} \times 6.0 \times 10^{-4} / 680$ ✓]

For the 2nd mark, allow use of viscous force calculation. Use of viscous force method does not get 1st mark.

$Q = 3.2 \times 10^{-19}$C ✓

If both methods are given and only one method gives Q = ne (where n = integer >1), ignore other method for 2nd mark and 3rd mark.

For the final mark, Q must be within n e ± 0.2×10^{-19} from a correct calculation.

3

(b) The weight of the second droplet is greater than the maximum electric force on it ✓

Alternative for 1st mark;

weight = drag force + elec force (owtte)

Scheme using V for next 5 marks;

If n =1 for the second droplet , pd to hold it = 1580 V (= *mgd / e*) ✓

which is not possible as V max = 1000 V ✓

If n = 2 , it would be held at rest by a pd of 790 V (= 1580 / 2 or 680 × 4.3 / 3.7 V) ✓

if n > 2 , it would be held at rest by a pd of less than 790 V (or 790 / n V) ✓

So n =1(e) must be the droplet charge ✓

Alternative schemes for last 5 marks

Q scheme *Using QV /d = mg for a stationary droplet gives Q = mgd / V =* $2.53 - 10^{-19}$ *C* ✓

which is not possible as Q = integer x e ✓

(so) Q (=ne) < 2.53×10^{-19} *C* ✓ *owtte)*

Calculation to show

Q= 1e fits above condition ✓

Q= 2e does not fit above condition ✓

F scheme*;- Calc of mg to give* $4.2 (\pm 0.2) \times 10^{-14}$ *N* ✓

Calc for Q = 1e of QV / d to give $2.6(\pm 0.2) \times 10^{-14}$ *N* ✓

Calc for Q =2e of QV / d to give $5.3 (\pm 0.2) \times 10^{-14}$*N* ✓

mg> elec force for Q =1e or <2e for Q=2e ✓

So n =1(e) must be the droplet charge ✓

Max 4

[12]

15 (a) (i) emission of (conduction) electrons from a heated metal (surface) or filament/cathode **(1)**
work done on electron = *eV* **(1)**

(ii) gain of kinetic energy (or ½ mv^2) = *eV;* rearrange to give required equation **(1)** 3

(b) (i) work done = force × distance moved in direction of force **(1)**
force (due to magnetic field) is at right angles to the direction of motion/velocity
[or no movement in the direction of the magnetic force
∴ no work done] **(1)**
electrons do not collide with atoms **(1)**

any two **(1)(1)**

[alternative for 1st and 2nd marks
(magnetic) force has no component along direction of motion **(1)**
no acceleration along direction of motion **(1)**
or acceleration perpendicular to velocity]

$r = \frac{mv}{Be}\left(or Bev = \frac{mv^2}{r}\right)$ **(1)**

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

$\therefore r^2\left(= \frac{m^2v^2}{B^2e^2}\right) = \frac{m^2}{B^2e^2} \times \frac{2eV}{m} = \frac{2mV}{B^2e}$ **(1)**

(iii) (rearranging the equation gives) $\frac{e}{m} = \frac{2V}{B^2r^2}$ **(1)**

$\frac{e}{m} = \frac{2 \times 530}{(3.1 \times 10^{-3})^2 \times (25 \times 10^{-3})^2} = 1.7(6) \times 10^{11}$ Ckg^{-1} **(1)**

7

[10]

16 (a) (i) unit A: supplies current/power/energy to the filament or heats the filament **(1)**
0 – 50 V **(1)**

(ii) unit B: to make the anode positive w.r.t. the filament, so that electrons are attracted/accelerated to the anode **(1)**
> 250 V **(1)**

max 3

(b) (i) beam current or intensity is reduced **(1)**
(because) fewer electrons are emitted (per sec) from the filament **(1)**
[or no beam as no electrons emitted if voltage of A
reduced enough **(1)**
(only)]

(ii) electrons travel faster [or more kinetic energy] **(1)**
(because the force of) attraction to the anode is greater **(1)**

4

[7]

17 (a) (i) weight [or force of gravity] pulls droplet down **(1)**
no electric force to counteract weight s **(1)**
viscous force increases with speed**(1)**
weight = viscous force at terminal speed**(1)**

(ii) viscous force = $6\pi\eta\, rv$ **(1)**

weight = $\frac{4}{3}\pi r^3 \rho g$ **(1)**

$\frac{4}{3}\pi r^3 \rho g = 6\pi\eta\, rv$ to give desired equation showing working **(1)**

max 6

(b) (i) $r^2 \left(= \frac{9\eta v}{2\rho g}\right) = \frac{9 \times 1.8 \times 10^{-5} \times 1.20 \times 10^{-3}}{2 \times 9.8 \times 950 \times 15.5}$ **(1)** (= 6.7×10^{-13} m^2)

$r = 8.2 \times 10^{-7}$ (m) **(1)**

$m \left(= \frac{4}{3}\pi r^3 \rho\right) = \frac{4}{3}\pi \times (8.2 \times 10^{-7})^3 \times 950$ **(1)** (= 2.2×10^{-15}` kg)

(ii) $\frac{QV}{d} = mg$ [or $Q = \frac{mgd}{V}$] **(1)**

$Q \left(= \frac{mgd}{V}\right) = \frac{2.2 \times 10^{-15} \times 9.8 \times 5.0 \times 10^{-3}}{225}$ **(1)**

$Q = 4.8 \times 10^{-19}$ **(1)**

6

(c) charge on oil droplet always a multiple of a basic amount **(1)**
basic amount = 1.6×10^{-19} C **(1)**
which is the charge of the electron **(1)**

max 2

[14]

18 (a) k.e. (= work done = qV [or $1.6 \times 10^{-19} \times 2200$]) = 3.5×10^{-16} J **(1)**

$\frac{1}{2} mv^2 = 3.5 \times 10^{-16}$ J

hence $v \left(= \sqrt{\frac{2 \times 3.5 \times 10^{-16}}{9.1 \times 10^{-31}}}\right) = 2.8 \times 10^7$ m s^{-1} **(1)**

(2)

(b) (i) all the k.e. goes to one photon **(1)**

hf = k.e. [or 3.5×10^{-16} J] **(1)**

$\lambda = \frac{c}{f}$ **(1)**

$= \frac{6.6 \times 10^{-34} \times 3 \times 10^{8}}{3.5 \times 10^{-16}}$ **(1)**

$= 5.7 \times 10^{-10}$ m **(1)**

(ii) $\lambda = \frac{h}{mv}$ **(1)**

$= \frac{6.6 \times 10^{-34}}{9.1 \times 10^{-31} \times 2.8 \times 10^{7}} = 2.6 \times 10^{-11}$ m **(1)**

(7)

[9]