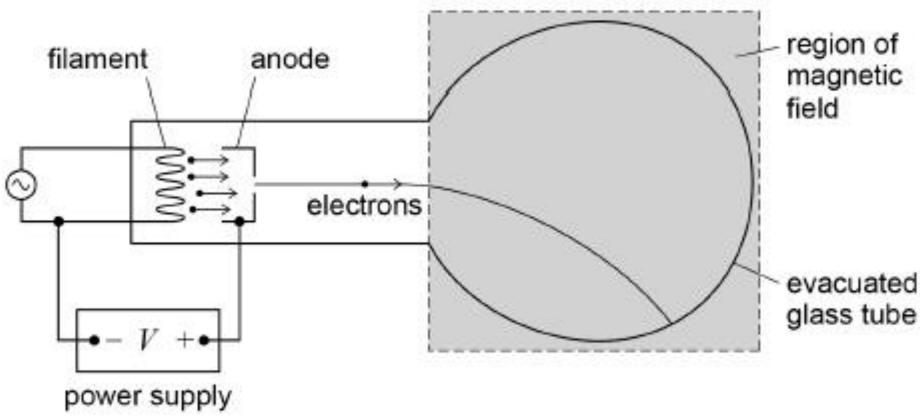
The discovery of electron

Q1.

The diagram shows apparatus which can be used to determine the specific charge of an electron.



Electrons are emitted from the filament and accelerated by a potential difference between the filament and anode to produce a beam. The beam is deflected into a circular path by applying a magnetic field perpendicular to the plane of the diagram.

(a) Describe the process that releases the electrons emitted at the filament.

____

(3)

(b) The table shows the data collected when determining the specific charge of the electron by the method shown in the diagram.

potential difference V that accelerates the electrons	320 V
radius r of circular path of the electrons in the magnetic field	4.0 cm
flux density B of the applied magnetic	1.5 mT

field	

Show that the specific charge of the electron is given by the expression $\frac{2V}{B^2r^2}$

(2)

(c) Using data from the table, calculate a value for the specific charge of the electron. Give your answer to an appropriate number of significant figures.

specific charge of the electron = ____________________ C kg^{-1}

(2)

(d) At the time when Thomson measured the specific charge of the particles in cathode rays, the largest specific charge known was that of the hydrogen ion.

State how Thomson's result for the specific charge of each particle within a cathode ray compared with that for the hydrogen ion and explain what he concluded about the nature of the particles.

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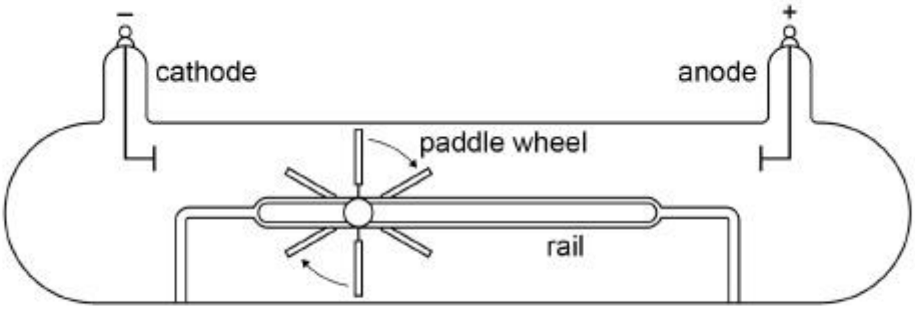
(2)

(Total 9 marks)

Q2.

The diagram shows a gas discharge tube devised by William Crookes in one of his investigations.

When a large potential difference is applied between the cathode and anode the paddle wheel is seen to rotate and travel along the rail towards the anode.



(a) Explain how this experiment led Crookes to conclude that cathode rays are particles and that these particles caused the movement of the paddle.

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(2)

(b) Later experiments showed that cathode rays are electrons in motion.

Explain how cathode rays are produced in a gas discharge tube.

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(3)

(c) In a particular gas discharge tube, air molecules inside the tube are absorbed by the walls of the tube.

Suggest the effect that this absorption may have on the motion of the paddle wheel.

Give a reason for your answer.

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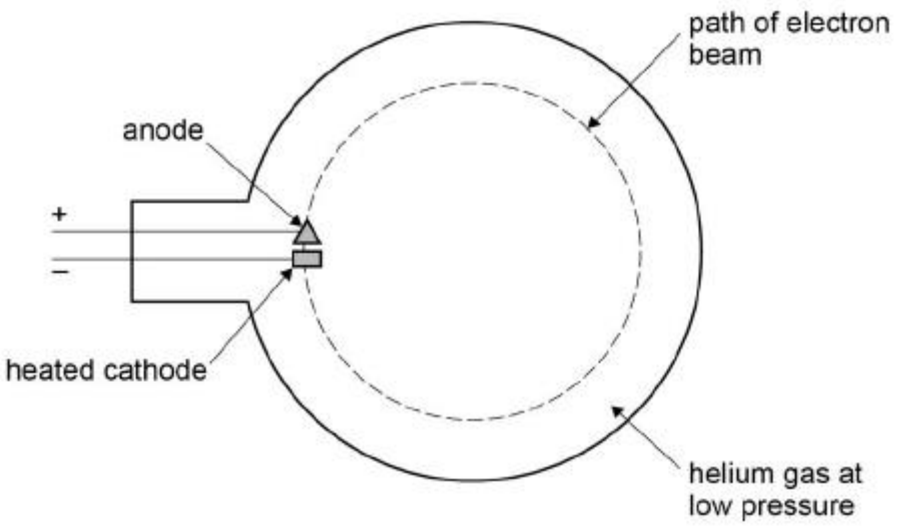
(2)

(Total 7 marks)

Q3.

The diagram below shows part of an apparatus used to determine the specific charge of an electron.



Electrons are emitted by the cathode by thermionic emission. They are accelerated by the potential difference between the cathode and anode. The tube contains helium gas at a low pressure and the gas emits light to show the path of the electron beam.

The beam is bent into a circular path by applying a magnetic field perpendicular to the plane of the diagram.

(a) Explain how light is emitted as the electrons travel through the helium gas.

(3)

(b) In one experiment the potential difference between the cathode and anode is 2.5 kV.

Show that the speed of the electrons is about 3.0×10^7 m s^{-1}.

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(2)

(c) When the flux density of the magnetic field is 3.1 mT the diameter of the path of the beam is 0.114 m.

Calculate the value for the specific charge of an electron from the data in this experiment.

specific charge ________________________ C kg^{-1}

(3)

(d) In practice the path of the electron beam is not a perfect circle.

Discuss how the presence of the gas affects the path of the electrons.

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(3)

(Total 11 marks)

Q5.

(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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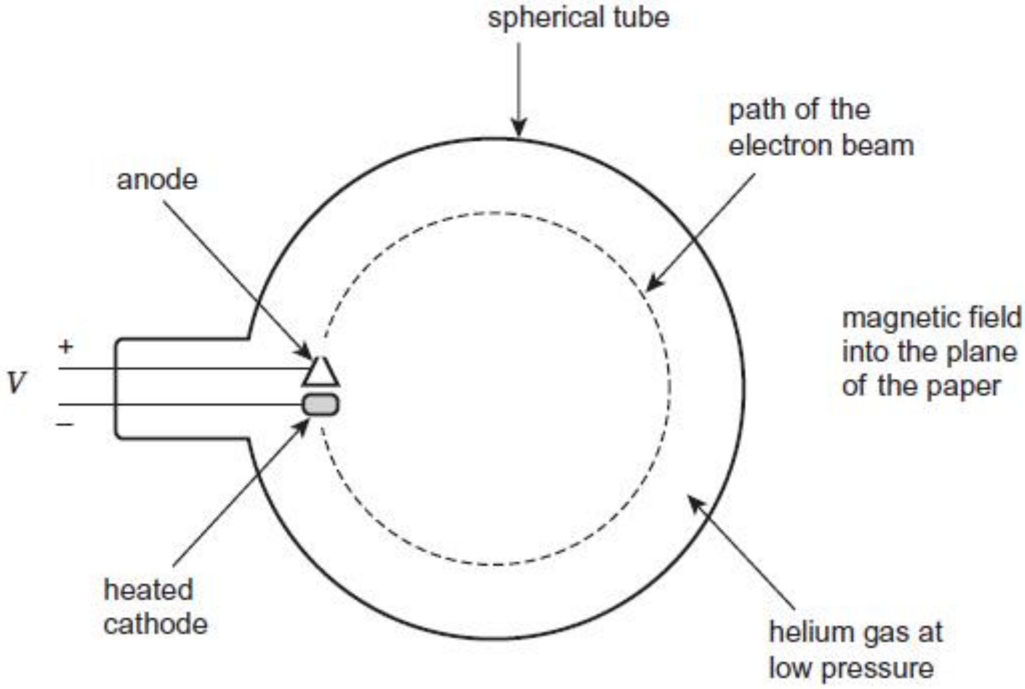
2. ____

(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.

(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.

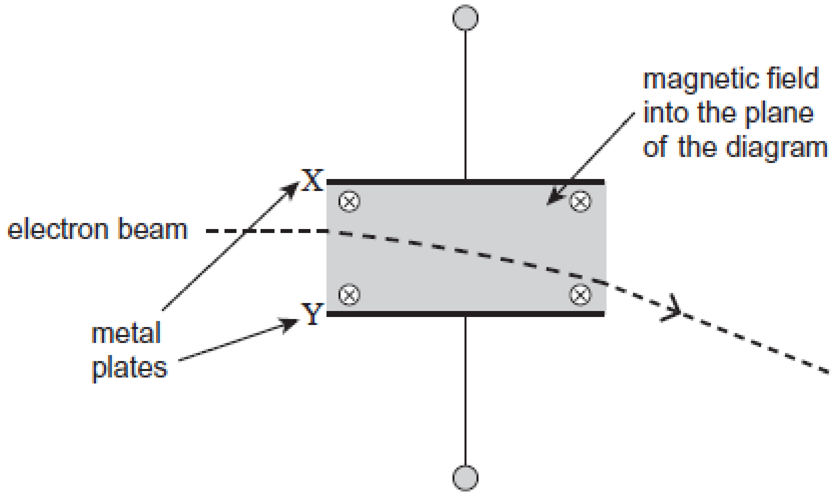
specific charge = ____________________ unit = ___________

(4)

(Total 9 marks)

Q6.

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)

Q1.

(a) Filament / metal is heated due to the current through it ✓

OR

Temperature of the filament rises due to the current through it

(Free / conduction) electrons gain sufficient/enough (kinetic) energy to leave (the metal surface)

OR

Work function (defines work function) ≤ energy supplied to an electron/electron energy ✓

Thermionic emission ✓

Not
Electrons are heated
Not heated due to the pd across it
Allow
By electrical power or electrically heated
Not allowed
Reference to electrons leaving <u>atoms</u> or ionisation
Allow
Energy supplied sufficient to overcome the work function

3

(b) Use one of $\frac{1}{2}mv^2 = eV$ and $r = \frac{mv}{Be}$ or $\frac{mv^2}{r} = Bev$

To arrive at

$\frac{Ber}{m} = v$ or $v = \sqrt{\frac{2eV}{m}}$ or $v^2 = \frac{2eV}{m}$

or $\frac{e}{m} = \frac{v}{Br}$ or $\frac{e}{m} = \frac{v^2}{2V}$ ✓

Substitution in the other equation and manipulates <u>correctly</u> and clearly to give $\frac{e}{m} = \frac{2V}{B^2r^2}$ ✓

Condone q for e
Substitution in other equation and correct manipulation
NB this is a show that so mark is not simply for stating the equation given
I presented such that v (velocity) and V (voltage) are indistinguishable in manipulation then award only first mark

2

(c) Correct substitution $\frac{e}{m} = \frac{2 \times 320}{(1.5 \times 10^{-3})^2 \times 0.040^2}$

And answer 1.8×10^{11} ✓

Answer to 2 sig figs ✓

Allow for incorrect answer following incorrect substitution in equation

As answer is on the data sheet must see correct substitution with all correct powers of ten

2

(d) The specific charge of the cathode rays/the particles was(much) larger/greater than the hydrogen ion/proton ✓

This provided evidence that cathode rays were composed of electrons/particles which have a (very) small mass / have a high (negative) charge

OR

Mass (much) smaller than the mass of a hydrogen (ion)/proton ✓

Not higher

If mark 1 not given then 0 for the question

Not lightest as substitute for mass

2

[9]

Q2.

(a) Cathode rays/electrons move from cathode toward anode

Accept move left to right.

1

The paddle wheel has gained energy from cathode rays/electrons. ✓

Accept as alternatives for energy kinetic,

energy/momentum/impulse ✓

Ignore references to force.

Ignore references to applying a magnetic field.

1

(b) Electrons are pulled out/escape from atoms OR gas atoms are ionised ✓

Condone molecules as alternative to atoms.

1

(Positive ions generated near the cathode are attracted to the cathode causing free) electrons emitted from the cathode.✓

1

Electrons are accelerated toward the anode (by the potential difference) ✓

Do not accept attraction as an alternative to acceleration.

1

(c) Reason: Idea of fewer electrons/cathode rays ✓

Effect: Paddle wheel rotates less ✓

Must score the reason mark to score the effect mark.

Ignore references to air resistance.

OR

Reason: Idea of electrons/cathode rays have higher energy/speed/momentum ✓

Effect: Paddle wheel rotates more ✓

If no mark is awarded, one mark can be awarded for the effect of the paddle wheel rotating more where the reasoning is limited to less collisions of electrons with air molecules.

2

[7]

Q3.

(a) Electrons collide with atoms.✓

Electron in an atom is excited into a higher energy level.✓

Emits a photon when the electron relaxes / moves to lower energy level.✓

3

(b) Substitutes in $eV = \frac{1}{2}mv^2$ ✓

Manipulates and gives answer to 2 or more sfs.✓

2

(c) Deduces *e/m* = *v/Br*.✓

Substitutes data (condone power of 10 errors).✓

$$\frac{e}{m} = \frac{3.0 \times 10^7}{3.1 \times 10^{-3} \times 5.7 \times 10^{-2}}$$

1.7×10^{11} (C kg^{-1}).✓

Substitution may come before manipulation.

3

(d) Electron velocity decreases when they collide.✓

v is proportional to *r*
OR *r* = *vm/Be* and *m*, *B* and *e* are constant.✓

r (gradually) decreases

or path with be an inwards spiral.✓

3

[11]

Q5.

(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) $eV = ½ mv^2$ and $\frac{mv^2}{r} = Bev$ or $\frac{e}{m} = \frac{v}{Br}$ in any form ✓
or $\frac{e}{m} = \frac{2V}{B^2r^2}$

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]

Q6.

(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 <u>and</u> the electron motion
Or
<u>direction</u> 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 $\frac{V}{B^2 rd}$

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]

Q1.

(a) Most students made some progress with this question (69.6% of students scored at least two marks). Those failing to be awarded the first marking point made no mention of the electrical heating *due to the current* in the filament. Many simply restated the stem, stating that electrons were emitted, without further detail. Thermionic emission was frequently mentioned in the response. Weak answers referred to electrons being “dragged” out of the filament by the positive anode.

(b) Presentation of the derivation was often very poor, with the space for the response being occupied by a jumble of equations that were unrelated. Over half of the students scored both marks, however. Whilst giving one correct equation with v as the subject was treated generously, students needed to produce an unambiguous and acceptable structured response to gain full credit. Questions of this type are common and it is expected that students should derive the given equation from more basic equations. It was **not** acceptable to substitute data in the given equation to produce a value that agreed with the accepted value for *e/m*. This was tested in part (c).

(c) Students needed to show all data substituted to gain full marks. Most appreciated that the answer needed to be given to two significant figures for consistency with the significant figures in the data used. 58.8% of students were awarded both marks.

(d) Weaker answers to this part referred to the greater specific charge for the electron meaning it was *smaller* rather than it having a lower mass. There was a high proportion of completely correct responses (54.4%) and nearly 80% of students scored at least one mark.

Q2.

(a) Although many students could identify the importance of the momentum carried by the particles in this question, not all went on to the explain that this momentum was transferred to the paddle wheel. A good number of students identified that the direction of travel of the cathode rays from cathode to anode was indicated by the direction of rotation of the paddle. Most students scored one of the two available marks, but few scored both.

(b) This question was not well answered by significant numbers of students. Common mistakes included describing the processes of thermionic emission and photon emission following de-excitation. A small number of students recalled, to a high level of detail, the process of ionisation and subsequent role of the positive ions in generating the electrons that go on to become cathode rays. A good number of students were able to describe the acceleration of the electrons toward the anode as an important factor in generating cathode rays.

(c) Responses to this question were good. Most students were able to explain how the lower number of air molecules would either reduce the electrons available to generate cathode rays, or result in the cathode rays present having more energy. Some students did not fully develop the latter argument to the point where cathode rays carried more energy, but were given some credit if they explained that collisions with air molecules would be reduced. A significant number of responses were limited to ideas about air resistance, which was not accepted.

Q5.

(a) This question required students to consider what could be inferred from the experiments described. Whilst there were some very good responses, many students answered using knowledge that came from different experiments which were performed later than the ones mentioned. Many, for example, quoted the magnitude of the electron's charge as a conclusion that could be drawn. This was measured by Millikan in 1909 whereas the experiments that led to the discovery of a subatomic particle (later becoming known as the electron) in the cathode rays, and earned Thomson a Nobel prize, were carried out in 1897.

(b) (i) This was often well done and there was a high proportion of well-expressed complete responses. Collisions of electrons with molecules rather than atoms was accepted for the first mark when discussing excitation and relaxation it was essential to mention that this takes place in an atom. A number of students stated that the nucleus was excited by the collisions. Some, even after stating that the excitation took place in atoms, went on to write that the subsequent emission was a gamma ray photon.

(ii) There were many completely correct responses in this part. Only a small minority of the students gave an incorrect unit. Some having quoted two appropriate equations failed to manipulate them correctly. Although they were instructed to 'use these data' a common error was to substitute in values for the electron charge an mass in $eV = \frac{1}{2} mv^2$ to find v and then use this in an equation to find e/m which defeats the objective of the experiment.

Q6.

(a) (i) A majority of the students identified the existence of a force perpendicular to the velocity but far fewer went on to explain the origin of the force.

Parts (ii), (iii) and (b) were generally very well done with students showing their initial equations and some evidence of manipulation.

(c) This proved to an accessible question with 35% of the students scoring 4 or more marks and nearly 90% scoring at least one mark. Weaker responses usually included some appropriate equations that are used in the determination but gave little to link them to the procedure. It was not always clear that a student knew that the same drop was used throughout the determination of a charge. Some stated explicitly that all drops were the same because they come from the same nozzle so having determined the radius in one experiment using terminal speed they used a different drop in the second part with the applied field. Other misunderstandings included reference to use of a magnetic field and referring to the charge on the drop as the specific charge.

The best responses identified at least in outline what was being done in the experiment. Relatively few explained how the terminal speed was determined but showed clearly how the equation for the radius was derived. These also went onto explain clearly how stopping the drops motion using an electric field led to the determination of the charge. The most common failing was not to identify the terms in the equations that were quoted or to identify them incorrectly. Some referred to the force $6\pi\eta rv$ as the viscosity and d in the equation $mg = VQ / d$ as 'the distance٦ or as 'the distance fallen٦.

Most strong and weak students made some reference to the charge being a multiple of 'e' although this was often vaguely linked to the experiment.