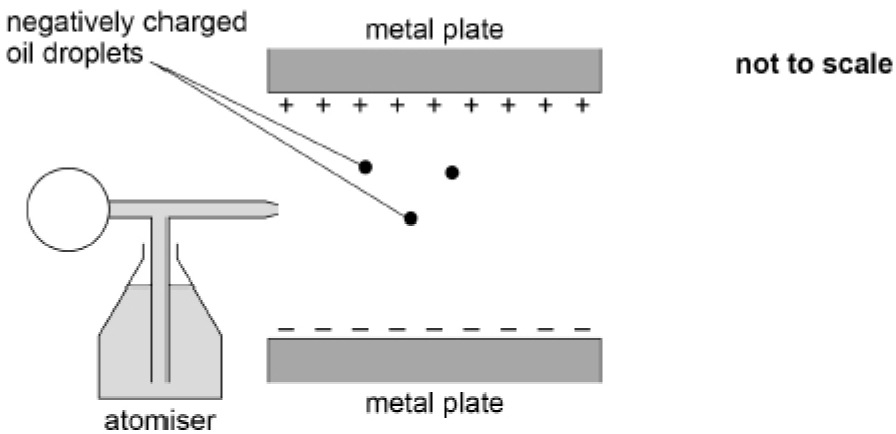
1. The diagram shows an experiment to measure the charge of the electron.



Negatively charged oil droplets are sprayed from the atomiser into the gap between the two horizontal metal plates. A potential difference is applied between the metal plates.

One of the droplets remains stationary.

(a) Identify the forces acting on the stationary droplet.
In your answer you should state the relationship between the forces.

The upthrust on the droplet due to the air it displaces is negligible.

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(2)

(b) The potential difference between the plates is changed to zero and the droplet falls at a terminal velocity of 1.0×10^{-4} m s^{-1}.

The density of the oil is 880 kg m^{-3}
The viscosity of air is 1.8×10^{-5} N s m^{-2}

Show that the radius of the droplet is about 1×10^{-6} m.

Assume that the droplet is spherical.

(3)

(c) The potential difference between the plates is restored to its initial value and the droplet becomes stationary.

The charge on the droplet is -4.8×10^{-19} C.

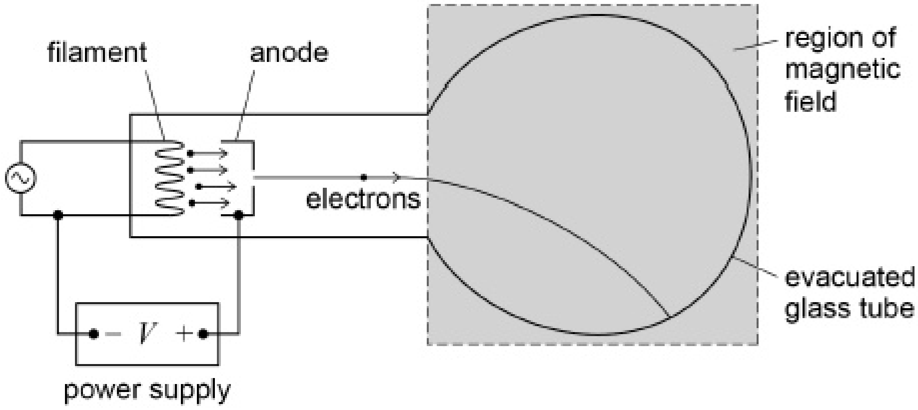
A student suggests that, if the droplet splits into two spheres of equal size, both spheres would remain stationary.

Deduce whether this suggestion is correct.

(3)

(Total 8 marks)

2. 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.

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(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 field	1.5 mT

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

(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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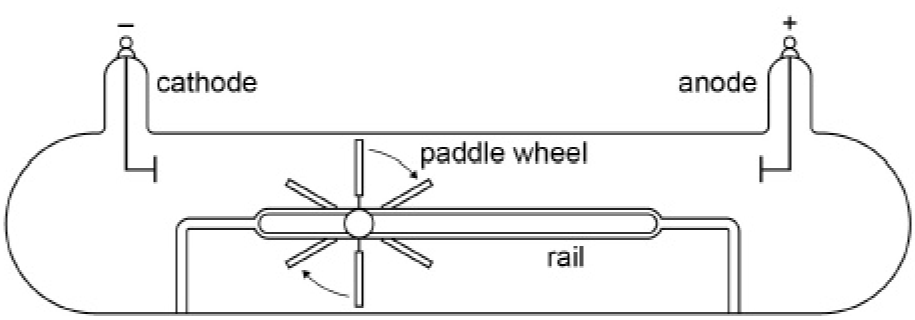
(2)

(Total 9 marks)

3. 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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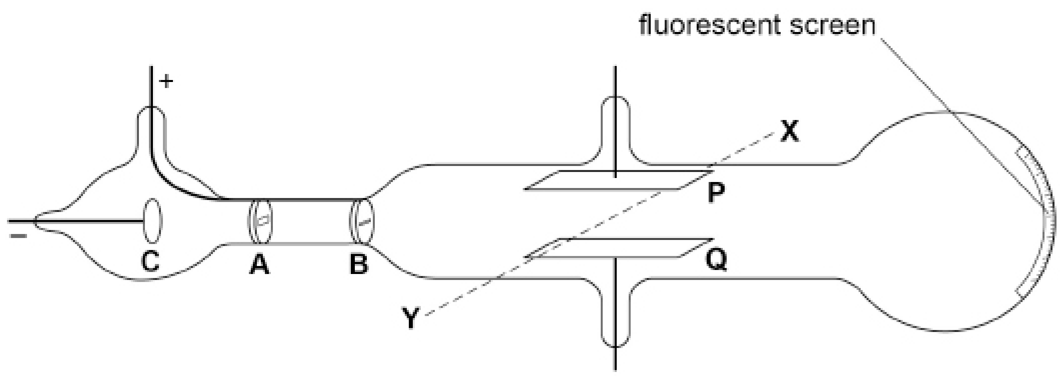
(2)

(Total 7 marks)

4. The figure shows a diagram of a discharge tube used by JJ Thomson to investigate cathode rays.



The direction **XY** is horizontal and at right angles to the axis of the tube.

(a) When correct connections are made to a high-voltage power supply, a cathode ray is produced. The cathode ray hits the centre of the fluorescent screen.

Describe how a cathode ray is produced in the discharge tube in the figure above.

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(2)

(b) **P** and **Q** are metal plates that can be attached to a second power supply.

In an experiment, a potential difference (pd) is applied across **P** and **Q** so that **P** is positively charged and **Q** is negatively charged. This deflects the cathode ray.

Then a magnetic field is applied between the plates so that the cathode ray follows its original path to the centre of the screen.

What is the direction of the magnetic field?
Tick (✓) **one** box.

from **P** to **Q** ☐

from **Q** to **P** ☐

from **X** to **Y** ☐

from **Y** to **X** ☐

(1)

(c) Changes are made to the apparatus so that the particles in the cathode ray travel with a greater speed as they pass between plates **P** and **Q**.

Explain how the cathode ray is restored to its original path by adjusting:

- only the electric field strength between **P** and **Q**
- only the magnetic flux density.

electric field strength only ____

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magnetic flux density only ____

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(3)

(d) Using the apparatus in the figure above, Thomson determined the specific charge of the particles in the cathode rays. Thomson compared this result with the specific charge of the hydrogen ion.

Discuss the significance of Thomson's results for the particles in cathode rays, when compared with the specific charge of the hydrogen ion.

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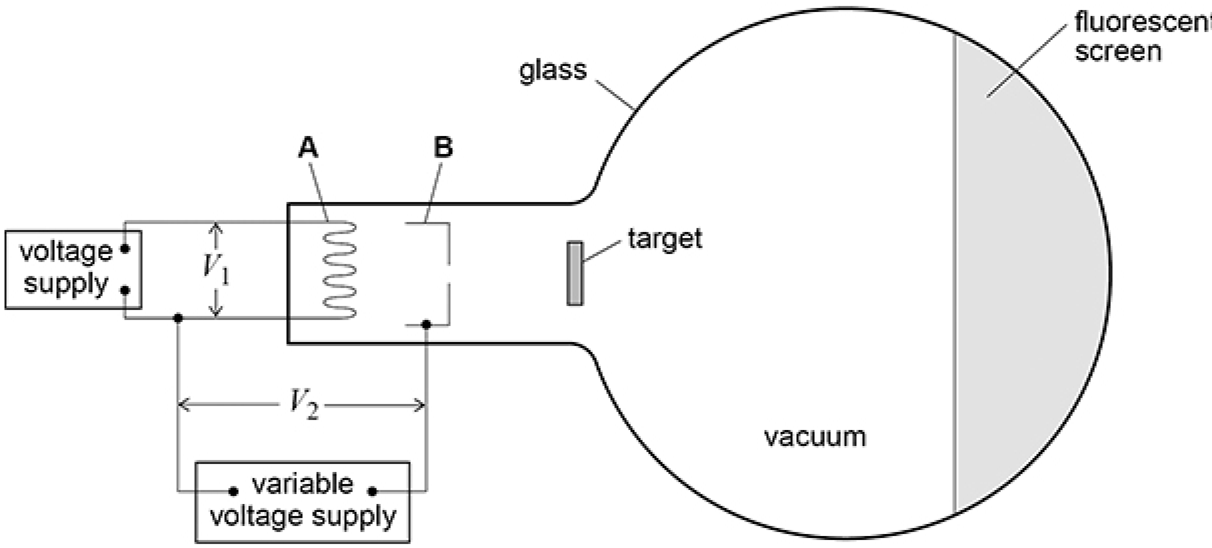
(2)

(Total 8 marks)

5. **Figure 1** shows the apparatus used in an experiment to investigate electron diffraction and the de Broglie hypothesis.

Figure 1



(a) Explain how high-speed electrons are produced in the apparatus in **Figure 1**.

In your answer you should:

- name parts **A** and **B**
- discuss the purposes of potential differences V_1 and V_2.

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(4)

(b) In the experiment, electrons are incident on a target made of a crystalline material. The electron wavelengths need to be about 50% the size of an atom to produce a diffraction pattern on the screen.

Suggest a suitable value for V_2.
Support your answer with a calculation.

V_2 = _______________ V

(4)

(c) **Figure 2** shows a typical diffraction pattern produced on the screen by the electrons.

Figure 2

Explain how measurements made with the apparatus in **Figure 1** can be used to support the de Broglie hypothesis.

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(4)

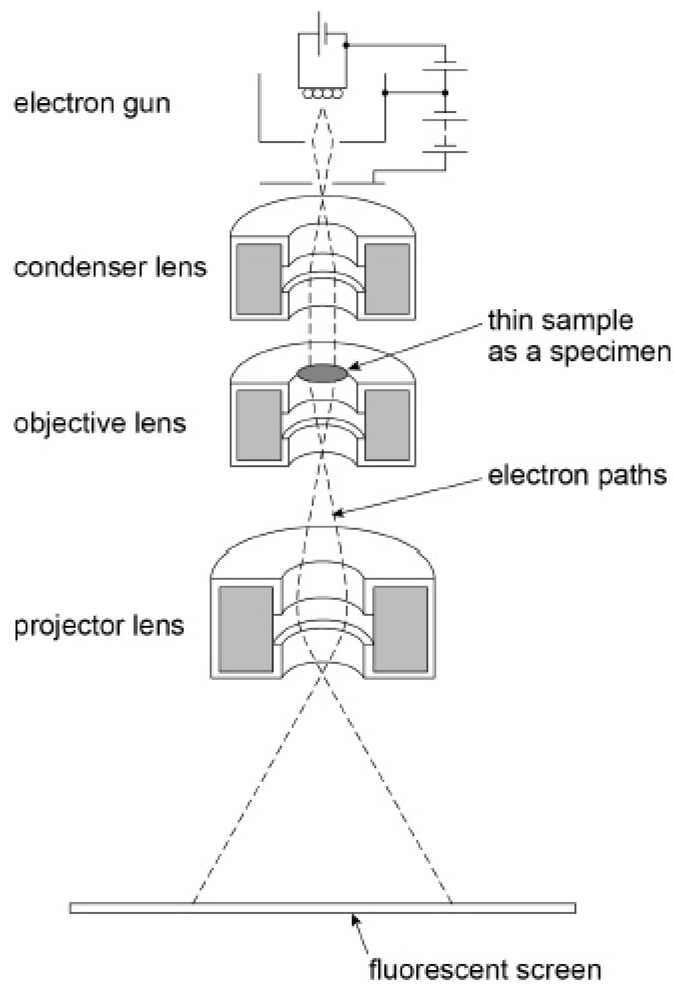
(d) STM and TEM are abbreviations for two types of electron microscope.

Which row links the type of microscope to a relevant property of moving electrons? Tick (✓) **one** box.

STM	TEM	
Moving electrons can cross a potential barrier.	Moving electrons can be deflected by a magnetic field.	☐
Moving electrons can be deflected by a magnetic field.	Moving electrons can be deflected by a magnetic field.	☐
Moving electrons can be deflected by a magnetic field.	Moving electrons can cross a potential barrier.	☐
Moving electrons can cross a potential barrier.	Moving electrons can cross a potential barrier.	☐

(1)
(Total 13 marks)

6. The diagram shows the main parts of a transmission electron microscope (TEM).



(a) What is the process by which electrons are produced in an electron gun?
Tick (✓) the correct box.

Beta particle emission ☐

Electron diffraction ☐

Photoelectric effect ☐

Thermionic emission ☐

(1)

(b) The electrons in a particular TEM have a kinetic energy of 4.1×10^{-16} J.
Relativistic effects are negligible for this electron energy.

Suggest, with a calculation, whether the images of individual atoms can, in principle, be resolved in this TEM.

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(3)

(c) A typical TEM can accelerate electrons to very high speeds and form high resolution images.

Explain:

- the process of image formation, and
- the factors that affect the quality of, and the level of detail in, the image.

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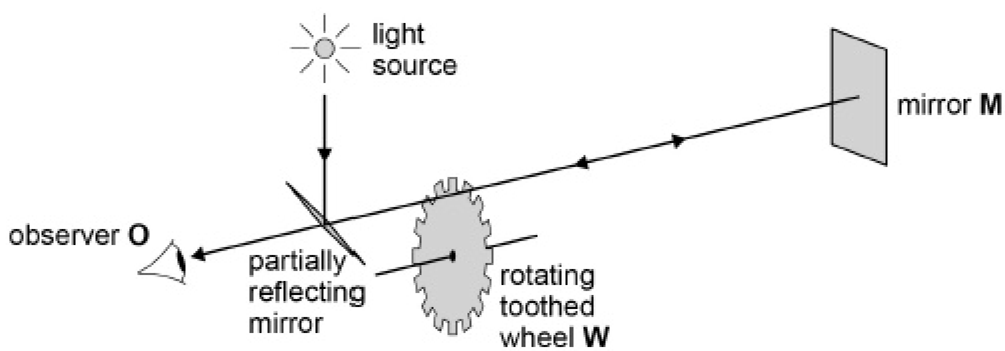
(6)
(Total 10 marks)

7. The diagram shows the apparatus Fizeau used to determine the speed of light.



The following observations are made.

A When the speed of rotation is low the observer sees the light returning after reflection by the mirror **M**.

B When the speed of the wheel is slowly increased the observer continues to see the light until the wheel reaches a certain speed. At this speed the observer cannot see the light.

(a) Explain these observations.

Observation A

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Observation B

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(2)

(b) The table shows data from Fizeau's experiment at the instant when observation B is made.

d, distance from **M** to **W**	8.6 km
f, number of wheel revolutions per second	12
n, number of teeth in the wheel	720

It can be shown that the speed of light c is given by the equation

$$c = 4dnf$$

Discuss whether the data in the table are consistent with the present accepted value for the speed of light.

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(2)

(c) The speed of the wheel is further increased.

Deduce the value of f when the observer would next be unable to see light returning from the mirror.

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(2)

(d) Explain how the nature of light is implied by Maxwell's theory of electromagnetic waves and Fizeau's result.

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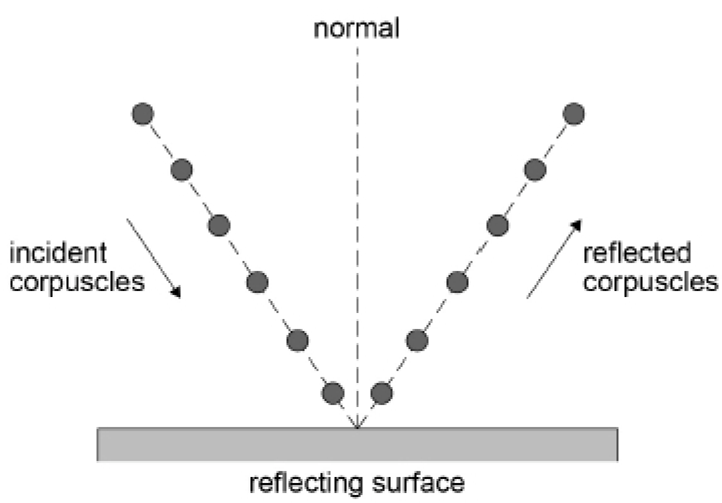
(3)
(Total 9 marks)

8. Newton used a corpuscular theory of light to explain reflection.

The diagram shows how corpuscles would reflect from a horizontal surface.



(a) What happens to the horizontal and vertical components of the velocity of the corpuscles, according to the theory, when they are reflected?

Tick (✓) **one** box.

Horizontal component of velocity	**Vertical component of velocity**	**Tick the correct box**
Unchanged	Changed	
Changed	Unchanged	
Unchanged	Unchanged	
Changed	Changed	

(1)

(b) Newton used the corpuscular theory to explain the refraction of light at an interface between air and water.

Huygens used the wave theory to explain the refraction of light at the interface.

Discuss the evidence that led to the rejection of Newton's corpuscular theory.

In your answer you should include

- how each theory explains refraction
- how experimental evidence led to the acceptance of the wave theory.

(6)

(c) Light is now known to behave as an electromagnetic wave.

Describe a plane-polarised electromagnetic wave travelling through a vacuum.
You may wish to draw a labelled diagram.

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(3)
(Total 10 marks)

9. **Figure 1** shows a modern version of the apparatus used by Hertz to investigate the properties of electromagnetic waves. Electromagnetic waves are continuously emitted from a dipole transmitter. The electromagnetic waves are detected by a dipole receiver.

An oscilloscope is used to display the amplitude of the detected signal at the dipole receiver.

Figure 1

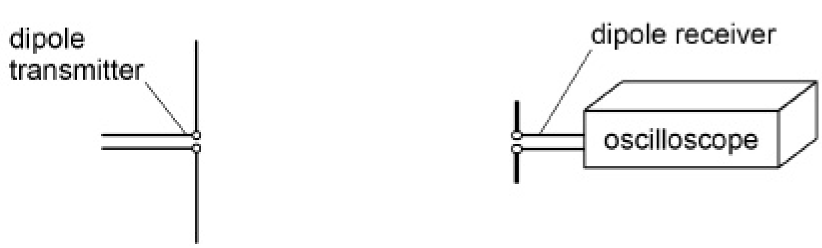
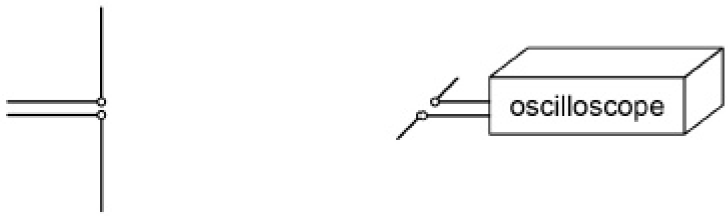


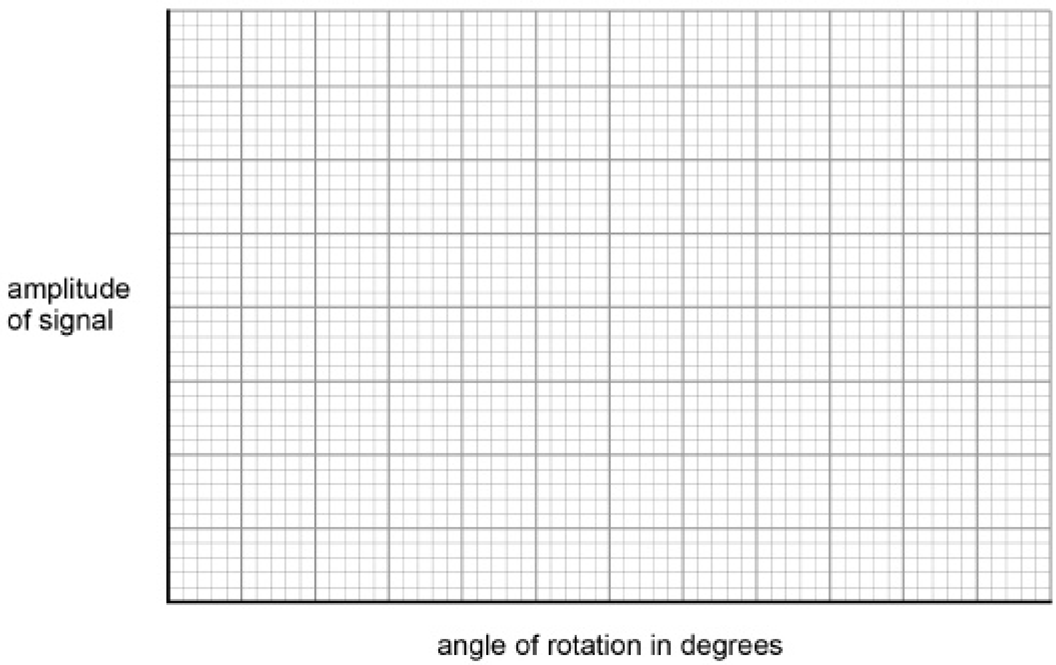
Figure 2 shows the same apparatus when the dipole receiver has been rotated through an angle of 90°

Figure 2



(a) Sketch a graph on **Figure 3** to show how the amplitude detected by the dipole receiver varies with angle of rotation as the receiver is turned through 360°
Start your graph from the position shown in **Figure 1**.

Figure 3



(3)

(b) Maxwell derived the equation $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$ for the speed c of electromagnetic waves,

where μ_0 is the permeability of free space and ε_0 is the permittivity of free space.

Explain, using a suitable calculation, why this equation led to the conclusion that light is an electromagnetic wave.

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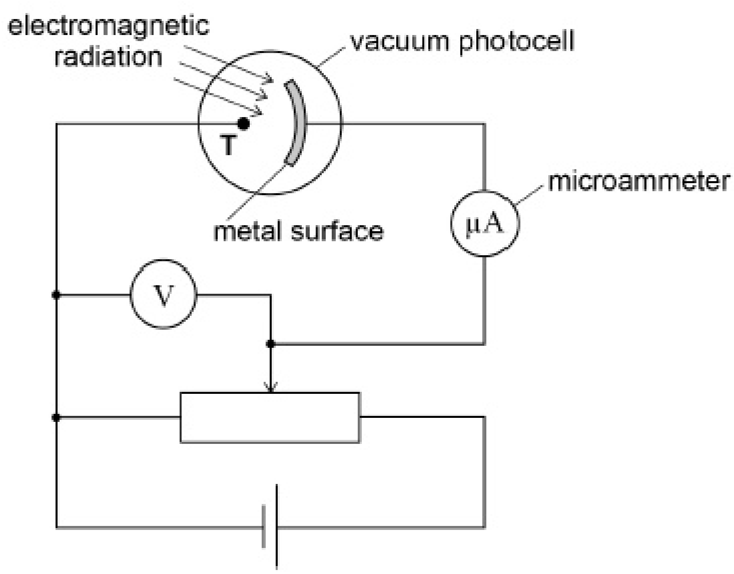
(2)

(Total 5 marks)

10. The diagram shows a vacuum photocell in which a metal surface is illuminated by electromagnetic radiation of a single wavelength. Electrons emitted from the metal surface are collected by terminal **T** in the photocell. This results in a photocurrent, I, which is measured by the microammeter.



The potential divider is adjusted until the photocurrent is zero.

The potential difference shown on the voltmeter is 0.50 V

The work function of the metal surface is 6.2 eV

(a) Calculate the wavelength, in nm, of the electromagnetic radiation incident on the metal surface.

wavelength = ____________________ nm

(3)

(b) The intensity of the electromagnetic radiation is increased. No adjustment is made to the potential divider.

The classical wave model and the photon model make different predictions about the effect on the photocurrent.

Explain the effect on the photocurrent that each model predicts and how experimental observations confirm the photon model.

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(3)

(c) The potential divider in the diagram is returned to its original position so that a photocurrent is detected by the microammeter.
The potential divider is then adjusted to increase the potential difference shown on the voltmeter.

Explain why the photocurrent decreases when this adjustment to the potential divider is made.

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(2)

(d) The apparatus shown in the diagram above is used to investigate three different metal surfaces **A**, **B** and **C**.
The table shows, for each of the three surfaces, a voltmeter reading V and the corresponding photocurrent I. The same source of electromagnetic radiation is used throughout the investigation.

	V/V	I/μA
Metal surface **A**	1.5	56
Metal surface **B**	2.5	56
Metal surface **C**	2.5	78

Which conclusion about the relationship between the work functions of **A**, **B** and **C** is correct?

Tick (✓) the correct box.

A > **B** > **C**.	☐
A < **B** < **C**.	☐
B > **A** > **C**.	☐
B < **A** < **C**.	☐

(1)

(Total 9 marks)

11. (a) The scanning tunnelling microscope (STM) uses a process called quantum tunnelling.

Explain what is meant by quantum tunnelling of an electron in an STM. You may include a diagram as part of your answer.

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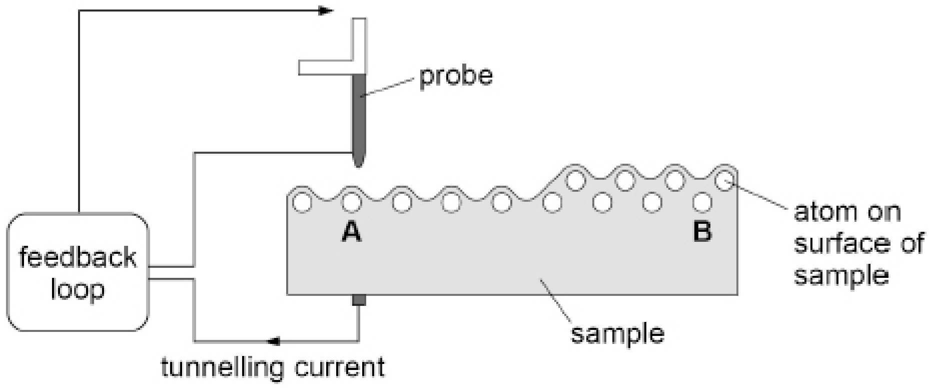
(2)

(b) An STM is used to map the positions of the atoms between points **A** and **B** on the surface of a sample.

The diagram shows some of the features of the operation of an STM.



The STM in the diagram above is in constant-current mode.

Describe how the STM creates a map of the positions of one row of atoms on the surface of the sample from **A** to **B**.

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(3)

(c) The smallest size of objects that the STM can resolve is similar to the de Broglie wavelength of the tunnelling electrons.

Deduce whether electrons with kinetic energies less than 1.5 eV are suitable to map the surface in the diagram above.

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(3)

(Total 8 marks)

12. In 1864, James Clerk Maxwell published a theory that included an equation for the speed of electromagnetic waves in a vacuum.

(a) Show that Maxwell's theory agrees with the accepted value for the speed of light in a vacuum.
Use information from the Data and Formulae Booklet in your answer.

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(2)

Between 1886 and 1889, Heinrich Hertz completed a series of experiments in an attempt to verify Maxwell's theory. **Figure 1** shows a simplified arrangement similar to the one used by Hertz in one of his experiments.

Figure 1

T is a radio wave transmitter with an aerial consisting of two vertical metal rods.
D is a detector that uses a conducting loop aerial.

(b) **T** is switched on so that an oscillating current is produced in the metal rods.
An emf is detected in the conducting loop aerial.

Explain this experiment with reference to Maxwell's model of electromagnetic waves.

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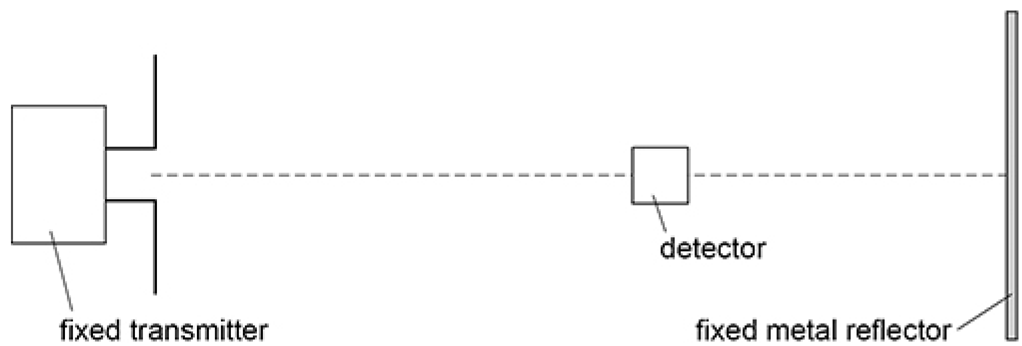
(4)

(c) In a different experiment Hertz used stationary waves to determine the speed of radio waves.
Figure 2 shows an experimental arrangement similar to the arrangement Hertz used.

Figure 2



Stationary waves are produced between the fixed transmitter and the fixed metal reflector.

In one experiment the distance between the transmitter and reflector is about 12 m and the transmitter frequency is 75 MHz.

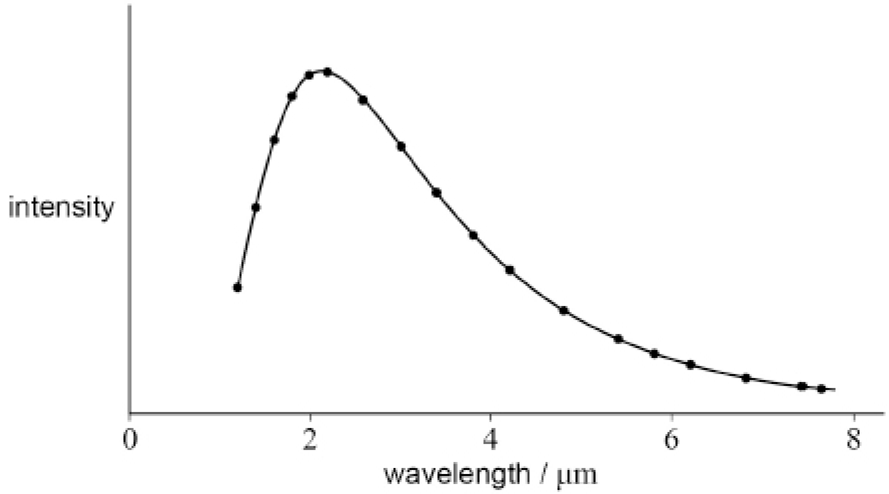
Deduce whether this arrangement can be used to measure the speed of electromagnetic waves suggested by Maxwell's equation.

(4)
(Total 10 marks)

13. At the end of the 19th century new information was obtained about black-body radiation and the photoelectric effect. This information challenged classical physics theories.

In 1895, Wien and Lummer carried out experiments to measure black-body radiation accurately.

The figure shows a typical black-body radiation curve of the type obtained by Wien and Lummer.



(a) State what is meant by black-body radiation.

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(2)

(b) Describe how the predictions of classical theory compare with Wien and Lummer's experimental results.

Annotate the figure above as part of your answer.

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(2)

(c) In 1900 Max Planck suggested a solution to the problems of the classical theory.

Outline the main aspects of his suggestion.

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(2)

(d) Planck's suggestion was developed by Albert Einstein to explain the results of photoelectric effect experiments.

Discuss Einstein's explanation of photoelectricity and its significance in terms of the nature of electromagnetic radiation.

In your answer you should

- describe **two** relevant observations made in photoelectric experiments
- explain the failure of classical physics to account for these observations
- include the main aspects of Einstein's theory and how he explained the observations.

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(6)

(Total 12 marks)