IB · HL · Physics

2 hours 13 questions

Structured Questions

Quantum Physics

The Photoelectric Effect (HL) / The Photoelectric Equation (HL) / The Particle Nature of Light (HL) / The de Broglie Wavelength (HL) / Wave-Particle Duality (HL) / Compton Scattering (HL)

Easy (5 questions)	/52
Medium (4 questions)	/45
Hard (4 questions)	/34
Total Marks	**/131**

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Easy Questions

1 (a) In an experiment to investigate the photoelectric effect, a beam of photons is incident on the surface of a metal.

State what is meant by the term photon.

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(2 marks)

(b) The photoelectric equation is given by:

$$hf = \phi + E_{k\ max}$$

Explain the meaning of each term in the photoelectric equation:

(i) hf

[1]

(ii) ϕ

[1]

(iii) $E_{k\ max}$

[1]

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(3 marks)

(c) Outline how Einstein's photon model is used to explain the photoelectric effect.

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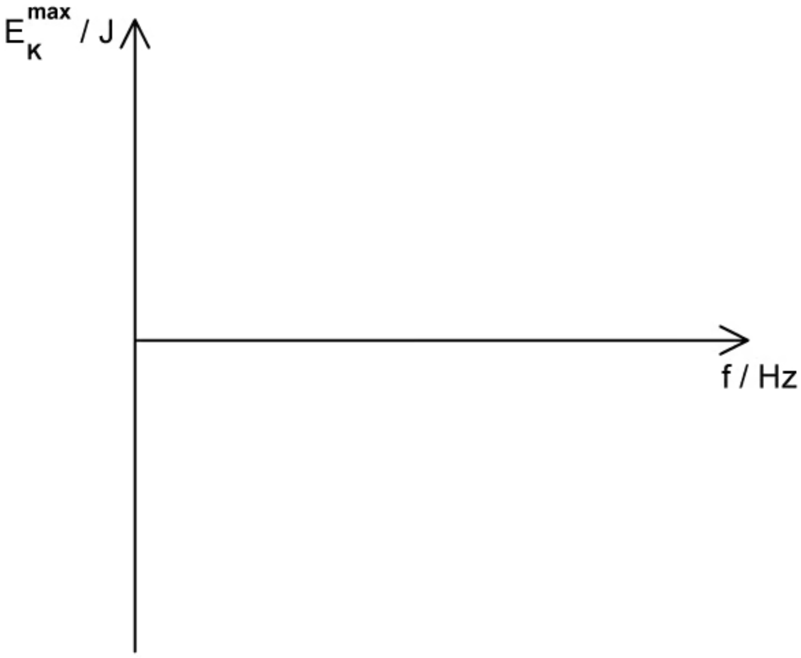
(3 marks)

(d) (i) Sketch a graph of $E_{K(max)}$ against f on the axes provided.

[2]



(ii) State the quantity represented by the gradient of the graph.

[1]

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(3 marks)

2 (a) Photons are emitted from an ultraviolet (UV) lamp and are incident on a metal photocathode.

Outline what happens at the metal photocathode when the photons are incident on its surface.

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(1 mark)

(b) No photoelectron emission is observed from the metal surface when the incident light is below a certain frequency.

Outline why the wave theory for light cannot explain this observation.

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(2 marks)

(c) The work function of the metal in the photocathode is 2.4 eV.

Outline what is meant by

(i) work function

[2]

(ii) threshold frequency

[2]

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(4 marks)

(d) The energy of the incident UV photons is 10.2 eV.

Calculate:

(i) The threshold frequency of the metal.

[2]

(ii) The maximum kinetic energy, in J, of the emitted electrons.

[2]

(4 marks)

3 (a) After the wave-particle duality of light had been confirmed by experiment, Louis de Broglie hypothesised the existence of matter waves.

Outline the de Broglie hypothesis.

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(2 marks)

(b) The de Broglie hypothesis was later confirmed in the Davisson-Germer experiment in which high-speed electrons were fired at a metal target and were found to scatter in a particular pattern.

State the phenomenon observed in this experiment and explain the evidence this provides about the nature of moving electrons.

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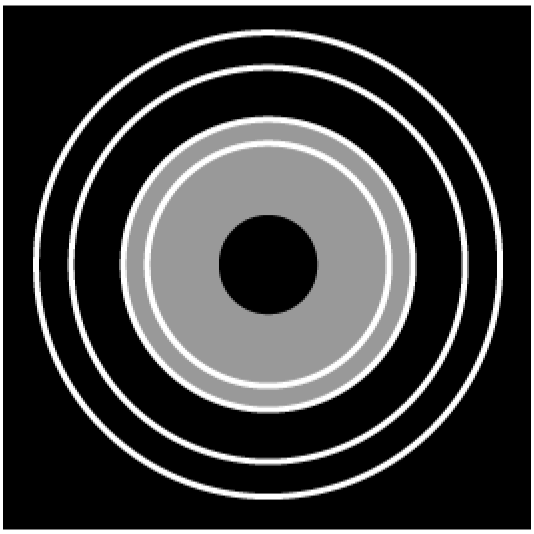
(2 marks)

(c) In a similar experiment, electrons fired at a thin graphite sheet are found to produce a pattern of concentric circles when they strike a fluorescent screen, as shown in the diagram.



Outline how the radius of the concentric rings would change if the speed of the electrons **decreases**.

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(1 mark)

(d) Calculate the de Broglie wavelength of an electron travelling at a speed of 3.18×10^7 m s^{-1}.

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(2 marks)

4 (a) The work function of sodium is 2.28 eV.

State what is meant by work function.

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(2 marks)

(b) The electronvolt is a unit of energy.

Show that 2.28 eV is equivalent to 3.65×10^{-19} J.

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(2 marks)

(c) State what is meant by the threshold frequency of a metal.

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(2 marks)

(d) Calculate the threshold frequency of sodium.

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(3 marks)

5 (a) The Compton effect is observed when a high-energy X-ray photon interacts with an orbital electron.

Outline what happens to the photon and electron in the Compton effect.

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(1 mark)

(b) An X-ray photon with initial wavelength 7.09×10^{-11} m scatters through an angle of 45°.

Calculate the change in

(i) photon wavelength

[2]

(ii) photon energy

[3]

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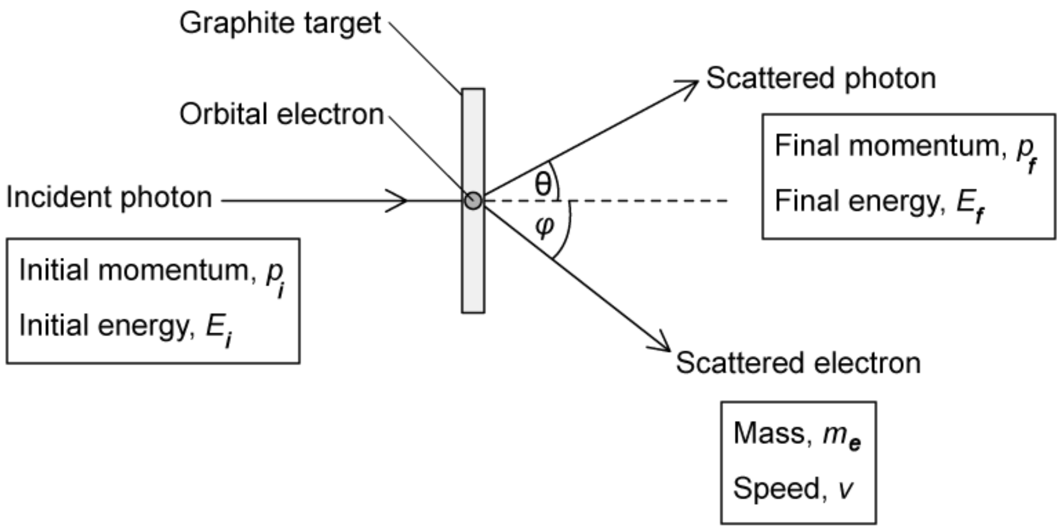
(5 marks)

(c) The collision between the incident X-ray photon and the stationary orbital electron is shown in the diagram.



For this interaction, write expressions for:

(i) the conservation of energy

[3]

(ii) the conservation of momentum.

[3]

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(6 marks)

(d) Explain why the scattered photon will have a longer wavelength than the wavelength of the incident photon.

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(2 marks)

Medium Questions

1 (a) When monochromatic light is incident on a clean metal surface, photoelectrons may be emitted through the photoelectric effect.

(i) Identify **one** feature of the photoelectric effect that cannot be explained by the wave theory of light.

[1]

(ii) Describe how this feature can be explained by the photon theory of light.

[2]

(3 marks)

(b) Explain why, although the incident light is monochromatic, the kinetic energies of emitted photoelectrons vary up to some maximum.

(3 marks)

(c) Explain why no photoelectrons are emitted if the frequency of the incident light is less than a certain value, no matter how intense the light.

(2 marks)

(d) For monochromatic light of wavelength 570 nm a stopping potential of 1.80 V is required for this particular metal surface.

Determine the minimum energy required to emit a photoelectron from the metal surface.

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(2 marks)

2 (a) Monochromatic light is incident on a metal surface and electrons are emitted instantaneously from the surface.

Explain why:

(i) electrons are emitted instantaneously.

[2]

(ii) the energy of the emitted electrons does not depend on the intensity of incident light.

[3]

(5 marks)

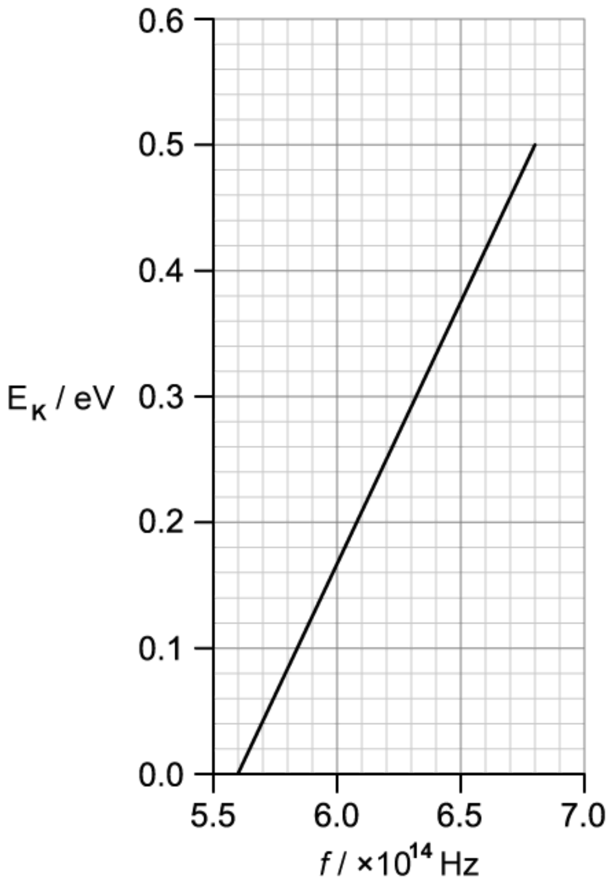
(b) The wavelength of light incident in part (a) is 450 nm and the work function of the metal is 2.0×10^{-19} J.

Determine the maximum kinetic energy of an electron emitted from the metal surface.

(2 marks)

(c) The light source used in part (b) is now incident on a different metal surface. Its frequency is varied, such that the kinetic energy of emitted electrons can be recorded.

The graph shows how the maximum kinetic energy E_K of the ejected electrons varies with the frequency of incident light.



Use the graph to determine a value for the Planck constant *h*.

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(2 marks)

(d) Use the graph in part (c) to determine the work function of the metal.

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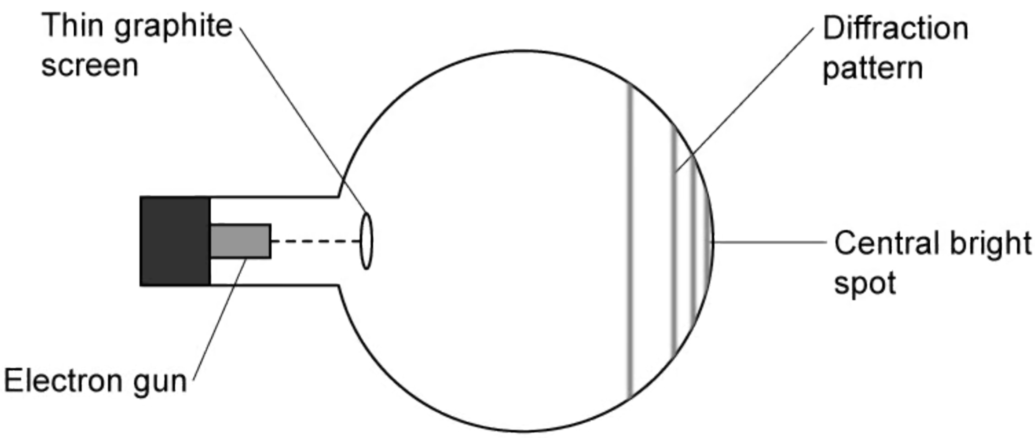
(2 marks)

3 (a) The diagram shows the end of an electron diffraction tube.



A pattern forms when diffracted electrons are incident on a fluorescent layer at the end of the tube.

Explain how the pattern demonstrates that electrons have wave properties.

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(3 marks)

(b) A particle accelerator produces a beam of electrons of energy 55 keV.

Calculate the de Broglie wavelength of an electron in the beam.

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(3 marks)

(c) Explain how the pattern in **(a)** changes with the momentum of the electrons.

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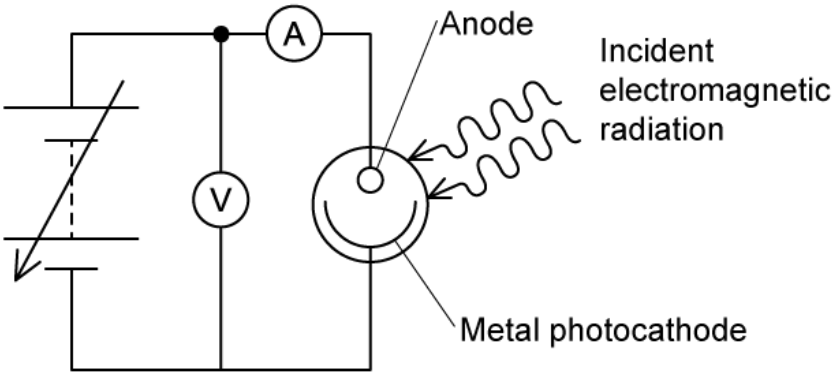
(3 marks)

(d) The separation between the carbon atoms in graphite is about 0.15 nm.

Discuss whether the electrons in **(b)** could be used to demonstrate diffraction using a thin piece of graphite.

(3 marks)

4 (a) Photons are incident on a metal photocathode as shown in the diagram.



Two key observations are made:

- Electrons are emitted from the surface of the plate when an ultraviolet source of weak intensity is used.
- Electrons are not emitted at all when a lamp emitting high-intensity visible light is used.

Explain these observations.

(4 marks)

(b) Hydrogen atoms in the ultraviolet (UV) source make transitions from the first excited state to the ground state.

Calculate the energy, in eV, of photons emitted from the UV source.

(3 marks)

(c) The work function of the photocathode metal is 2.3 eV.

Calculate the maximum kinetic energy of electrons, in J, emitted from the surface of the metal.

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(2 marks)

(d) Calculate the shortest de Broglie wavelength of the emitted electrons.

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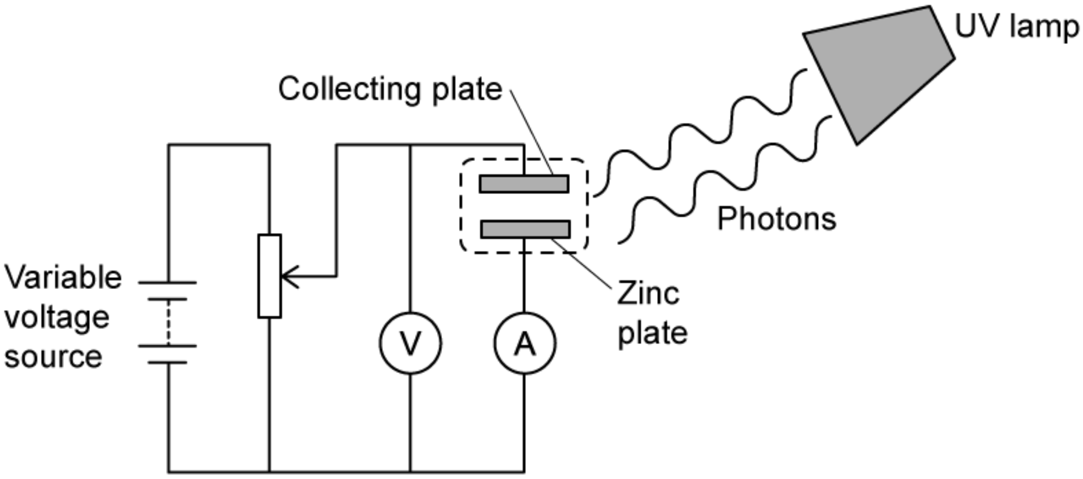
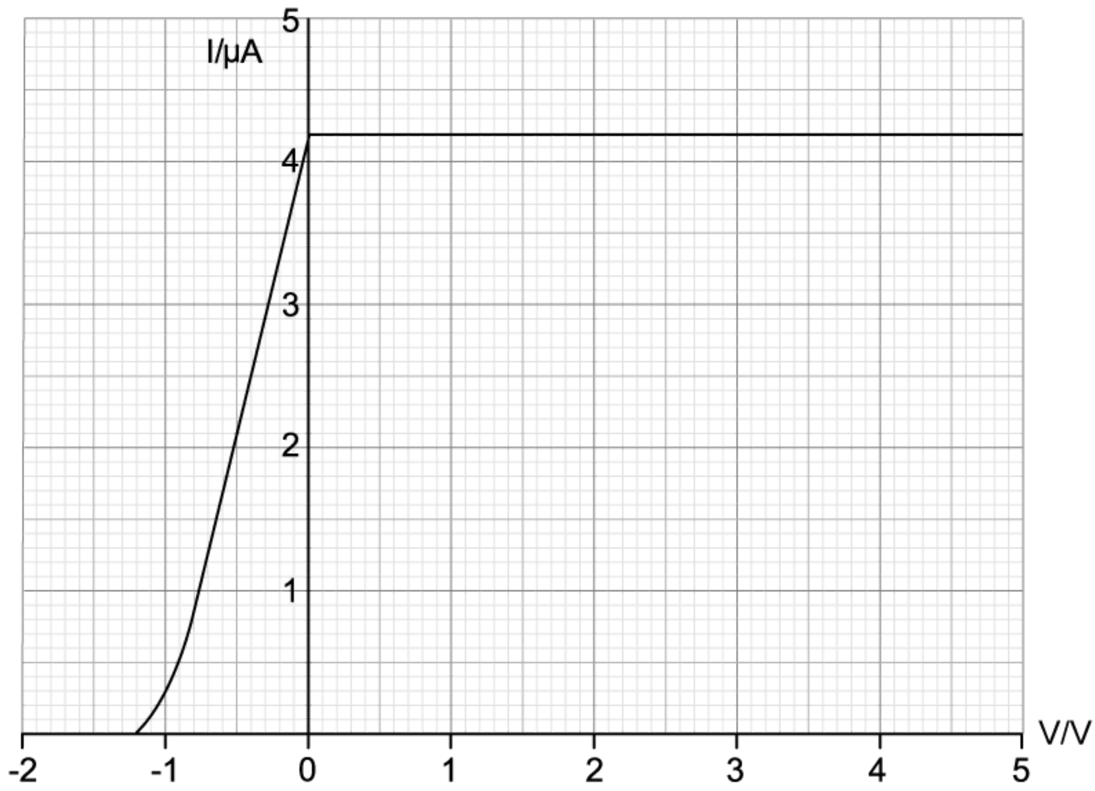
(3 marks)

Hard Questions

1 (a) Ultraviolet light is incident on a zinc plate. The zinc plate is situated within an evacuated chamber a few millimetres under a collecting plate, as shown in the diagram.



Photoelectrons are emitted from the zinc plate and move towards the positive collecting plate due to the potential difference, V, between the plates. When the potential difference, V, is varied, it is observed that the photoelectric current varies as shown on the graph.



(i) Explain why the photoelectric current reaches a maximum value despite further increases in potential difference.

[2]

(ii) The battery connections are reversed so that the potential difference across the plates is negative. As a result, the photoelectrons are now repelled by the collecting plate, although some still make it across.

Explain this observation.

[2]

(4 marks)

(b) The experiment is repeated by using a different ultraviolet lamp which has a lower intensity and wavelength.

(i) Sketch a second curve on the graph in part (a) to show the new variation between photoelectric current and potential difference.

[2]

(ii) Explain the difference between the two graphs.

[2]

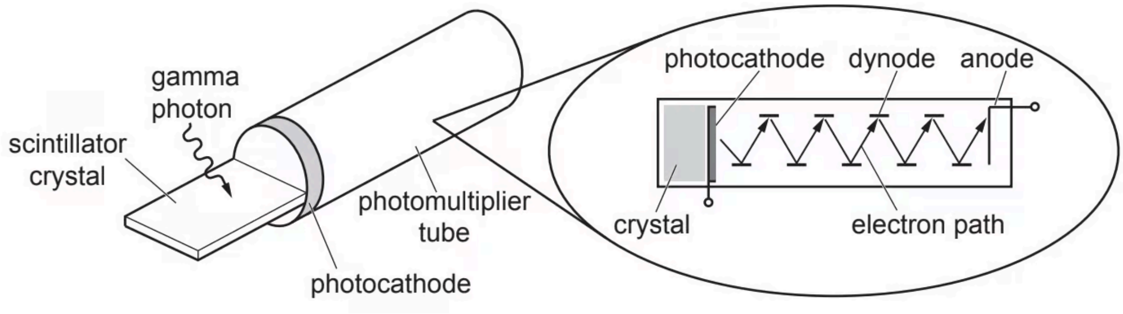
(4 marks)

(c) The work function of zinc is 3.74 eV.

Determine the wavelength of the ultraviolet light incident on the zinc plate.

(4 marks)

2 (a) The diagram shows a single photomultiplier tube and its internal components. The tube can detect gamma photons in high-energy physics experiments.



A single gamma photon incident on the scintillator crystal generates many photons of blue light. These visible light photons travel to the photocathode where they are converted into photoelectrons.

The number of electrons is then multiplied in the photomultiplier tube with the help of electrodes called dynodes. A short pulse of electric current is produced at the output end of the photomultiplier tube.

A high energy gamma photon passing through the scintillator crystal converts some of its energy into visible light photons of mean wavelength 450 nm.

Show that the energy of a single photon of wavelength 450 nm is less than 3 eV.

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(2 marks)

(b) The photocathode is coated with potassium which has a work function of 2.3 eV. Each emitted photoelectron is accelerated by a potential difference of 100 V between the photocathode and a metal plate, called the first dynode.

(i) Show that the maximum kinetic energy of an emitted electron at the photocathode is very small compared to its kinetic energy of 100 eV at the first dynode.

[1]

(ii) 2000 photoelectrons are released from the photocathode. Each photoelectron has enough energy to release four electrons from the first dynode at the collision. These four electrons are then accelerated to the next dynode where the process is repeated. There are 9 dynodes in the photomultiplier tube. The total number of electrons collected at the anode for each photoelectron is 4^9. The pulse of electrons at the anode lasts for a time of 2.5×10^{-9} s.

Calculate the average current due to this pulse.

[3]

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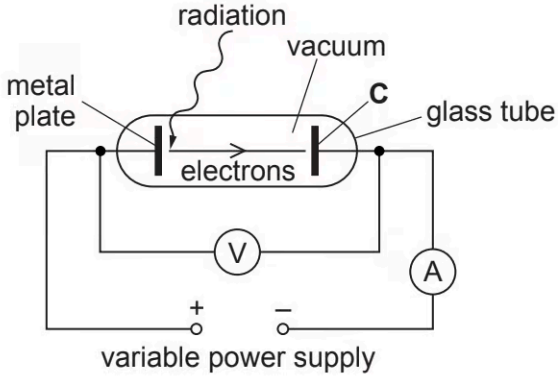
(4 marks)

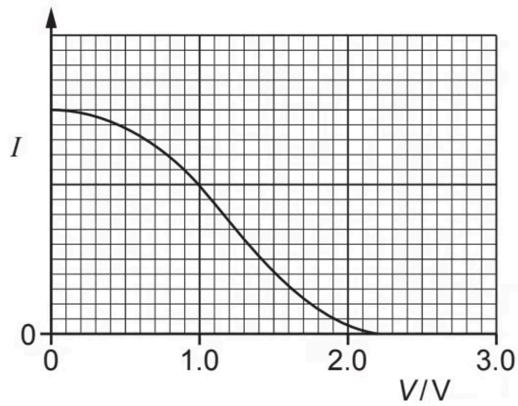
(c) Electromagnetic radiation of constant wavelength is incident on a metal plate. Photoelectrons are emitted from the metal plate.

The diagram shows an arrangement used to determine the maximum kinetic energy of electrons emitted from a metal plate.



The metal plate and the electrode **C** are both in a vacuum. The electrode **C** is connected to the negative terminal of the variable power supply.

The graph shows the variation of current I in the circuit as the potential difference V between the metal plate and **C** is increased from 0 V to 3.0 V.



Explain why the current decreases as V increases and describe how you can determine the maximum kinetic energy of the emitted electrons.

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(3 marks)

3 (a) The concept of solar sails has been proposed as a means of propelling spacecraft around the Solar System. They would operate using the momentum of solar photons as they reflect from the gigantic low-mass sails.

At Earth, a parallel beam of light with wavelength 550 nm is incident normally on the surface of a solar sail.

Determine the rate of photons striking 1.0 m^2 of the surface every second.

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(3 marks)

(b) Show that the force exerted by the reflection of photons on a 1.0 m^2 surface of the solar sail is about 9×10^{-6} N.

Assume that the Sun's rays are normal to the sail and all the radiation is reflected.

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(2 marks)

(c) A solar sail fixed to a spacecraft of mass 200 kg, with the full area of the sail facing the Sun, achieves an acceleration of 1.2 mm s^{-2}.

Determine the area of the solar sail.

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(3 marks)

4 (a) The absorption and scattering of X-rays by matter can be used to investigate the structure and composition of a material. One of these scattering processes is known as Compton scattering.

In Compton scattering, an incident photon of frequency f collides elastically with a stationary electron. A scattered photon is produced with a frequency of $f - \Delta f$ and moves away at an angle of θ to the direction of the incident photon.

The electron of mass m_e moves away with speed v.

By considering the conservation of energy of the collision, show that

$$m_e v^2 = 2h\Delta f$$

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(2 marks)

(b) Both the photoelectric effect and the Compton effect demonstrate that light behaves as if it were composed of particles.

Discuss which phenomena provides the most convincing evidence of the particle nature of light.

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(3 marks)