IB · DP · Physics

3 hours 15 questions

Structured Questions

12.1 The Interaction of Matter with Radiation

12.1.1 Photons / 12.1.2 The Photoelectric Effect / 12.1.3 Observing the Photoelectric Effect / 12.1.4 Solving Photoelectric Problems / 12.1.5 Matter Waves / 12.1.6 Pair Production & Annihilation / 12.1.7 Quantization of Angular Momentum / 12.1.8 The Wave Function / 12.1.9 The Uncertainty Principle / 12.1.10 Tunnelling

Easy (5 questions)	/58
Medium (5 questions)	/51
Hard (5 questions)	/75
Total Marks	**/184**

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Easy Questions

1 (a) In an experiment to investigate the photoelectric effect, a constant number of photons is incident on a photo-surface.

State what is meant by the term photon.

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(1 mark)

(b) The photoelectric equation is given by:

$$hf = \phi + \frac{1}{2}mv^2_{max}$$

Explain the meaning of each term in the photoelectric equation:

(i) hf

[1]

(ii) ϕ

[1]

(iii) $\frac{1}{2}mv^2_{max}$

[1]

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(3 marks)

(c) (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]

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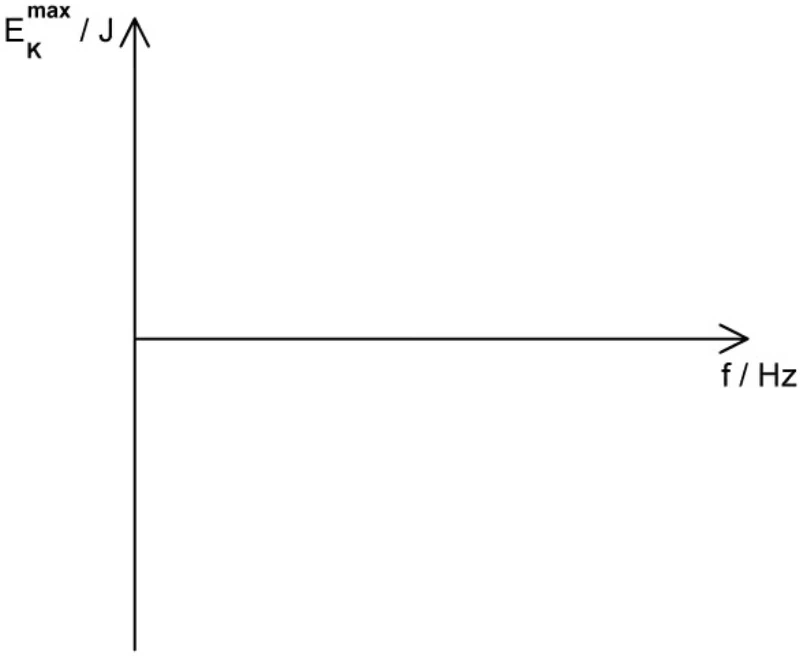
(3 marks)

(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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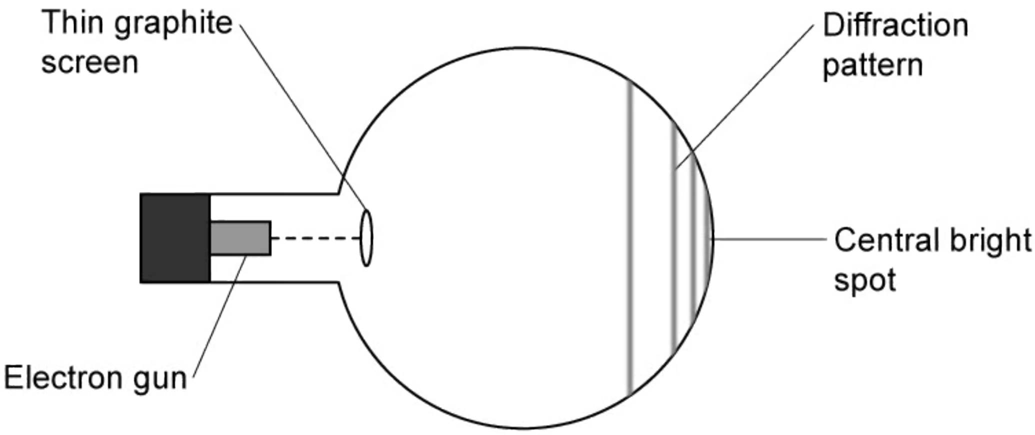
(3 marks)

2 (a) 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) The de Broglie wavelength λ of a particle accelerated close to the speed of light is approximately

$$\lambda \approx \frac{hc}{E}$$

Where E is the energy of the particle.

A beam of electrons is produced in a particle accelerator with energy 3.1×10^8 eV.

Calculate the wavelength of an electron in the beam.

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(3 marks)

(c) State what can be deduced about an electron from the amplitude of its associated wavefunction.

(2 marks)

(d) Heisenberg's uncertainty principle can be expressed as:

$$\Delta x \Delta p \geq \frac{nh}{2\pi}$$

An electron reaching the central bright spot on the fluorescent screen has a small uncertainty in its position.

(i) Outline the meaning of each quantity in Heisenberg's uncertainty principle.

[2]

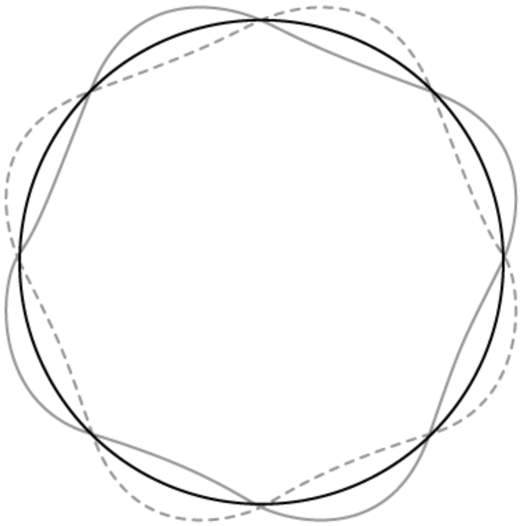
(ii) Describe what the Heisenberg uncertainty principle is able to predict about another property of this electron.

[1]

(3 marks)

3 (a) In a hydrogen atom, an electron of mass *m* orbits the proton with speed *v* in a circular orbit of radius *r*.

The diagram shows an electron wave in hydrogen.



(i) State the meaning of the term electron wave.

[1]

(ii) Identify the number of allowed electron orbits shown in the diagram.

[1]

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(2 marks)

(b) By equating the centripetal and electric forces acting on the electron, show that the speed *v* of an electron in the hydrogen atom is related to the radius *r* of its orbit by the expression

$$v = \sqrt{\frac{ke^2}{m_e r}}$$

....

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(3 marks)

(c) Using your answer to (b) and the Bohr condition, deduce that the radius *r* of the electron's orbit in the n level of hydrogen is given by the following expression:

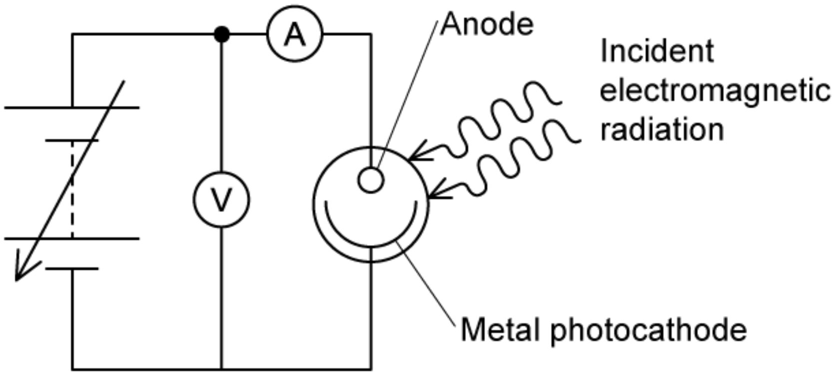
$$r = \frac{n^2 h^2}{4\pi^2 k m_e e^2}$$

(3 marks)

(d) Calculate the electron's maximum orbital radius, *r*.

(3 marks)

4 (a) Hydrogen atoms in an ultraviolet (UV) lamp make transitions from the first excited state to the ground state. Photons are emitted and are incident on a metal photocathode as shown.



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

[1]

(ii) Calculate the energy, in eV, of photons emitted from the UV lamp.

[3]

(4 marks)

(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.

(2 marks)

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

Outline the meaning of the terms:

(i) Work function

[2]

(ii) Threshold frequency

[2]

(4 marks)

(d) Calculate:

(i) The threshold frequency of the metal.

[2]

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

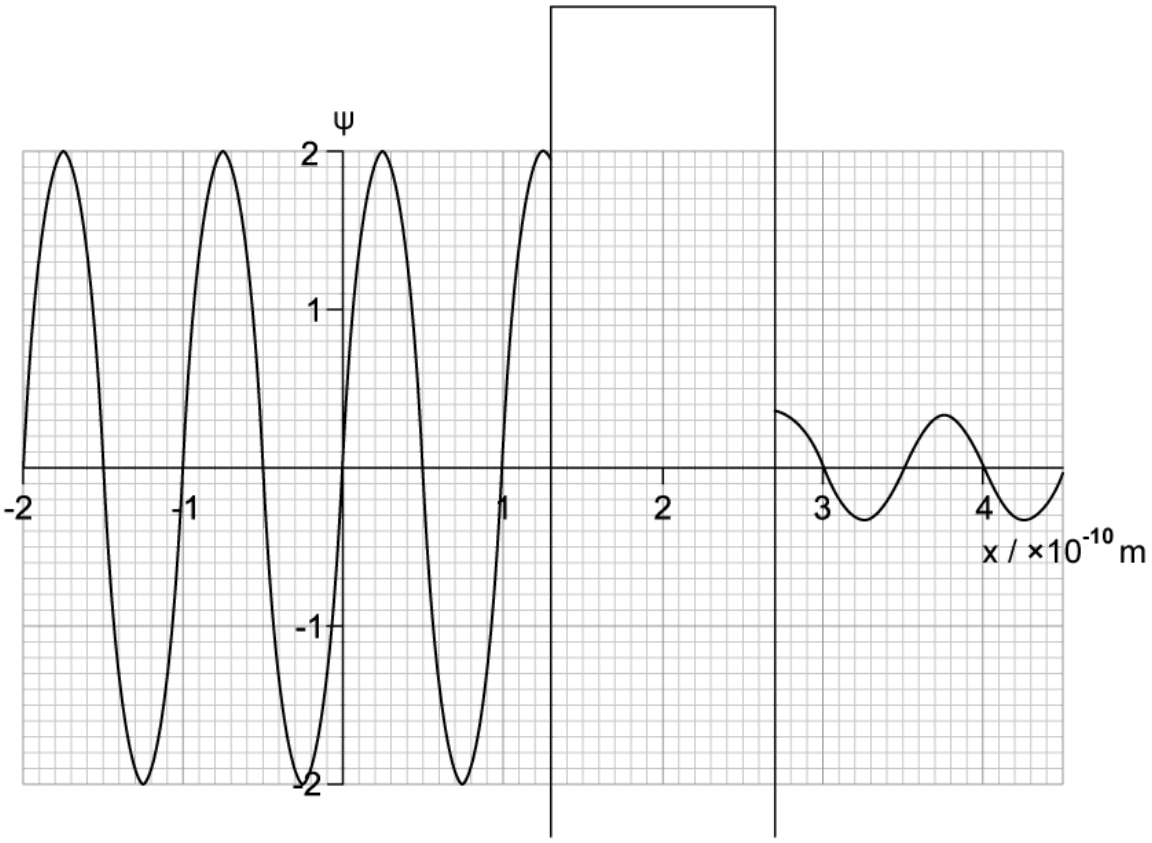
[2]

(4 marks)

5 (a) State what is meant by quantum tunnelling, and give an example of its application or natural occurrence.

(3 marks)

(b) The graph shows the wavefunction, Ψ, of electrons that undergo tunnelling through a potential barrier.



Complete the graph by showing how the wavefunction propagates through the barrier.

(2 marks)

(c) Use the graph in (b) to determine:

(i) The width of the barrier, in m.

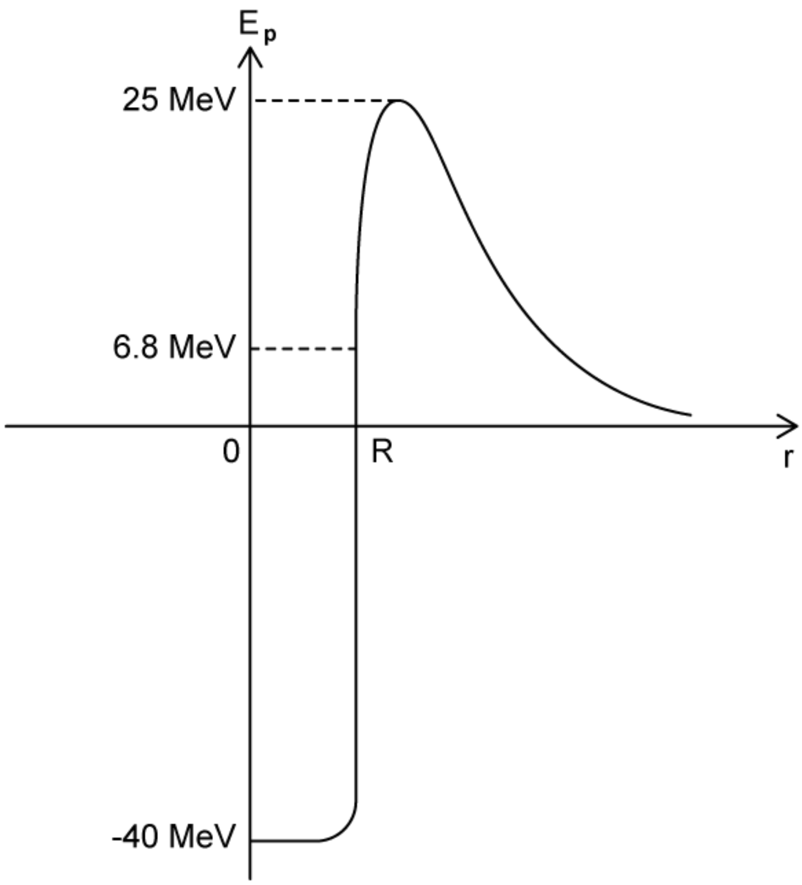
[1]

(ii) If the kinetic energy of the electrons changes after tunnelling.

[2]

(3 marks)

(d) The diagram shows the variation of the potential energy of an alpha particle with distance from the nuclear centre. The nuclear radius is R. The total energy of an alpha particle within the nucleus is 6.8 MeV.



(i) State the significance of the value 25 MeV.

[1]

(ii) On the graph, draw a line to show the path of the alpha particle when the nucleus decays, and indicate the "classically forbidden region" on the path.

[2]

(iii) The probability of an alpha decay occurring can vary from 10^{-7} s to 10^{10} years depending on the nucleus. State the quantity used in nuclear physics that this time represents.

[1]

(4 marks)

Medium Questions

1 (a) Describe what is meant by the wave function of an electron.

(2 marks)

(b) An electron is confined in a finite region of length 6.8×10^{-14} m.

Determine the uncertainty in the momentum of the electron.

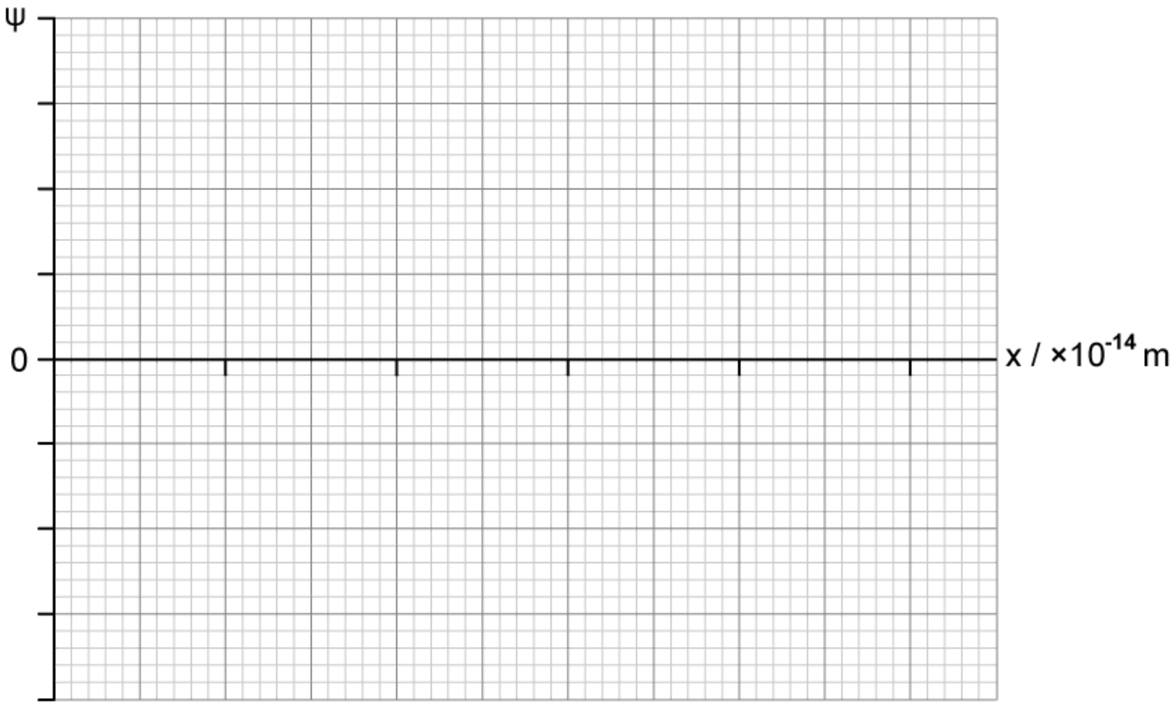
(2 marks)

(c) Determine the associated de Broglie wavelength of the electron if it was accelerated into its confinement through a potential difference of 5.5 GV.

(2 marks)

(d) On the axes provided, sketch the wave function Ψ of the electron described in part (b) and (c) with distance x.

You may assume that $\Psi = 0$ when $x = 0$.



(4 marks)

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

Outline how Einstein's model is used to explain the photoelectric effect.

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(3 marks)

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

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(2 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.

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(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)

3 (a) Outline the de Broglie hypothesis.

(2 marks)

(b) Explain why a precise knowledge of the de Broglie wavelength of an electron implies that its position cannot be measured.

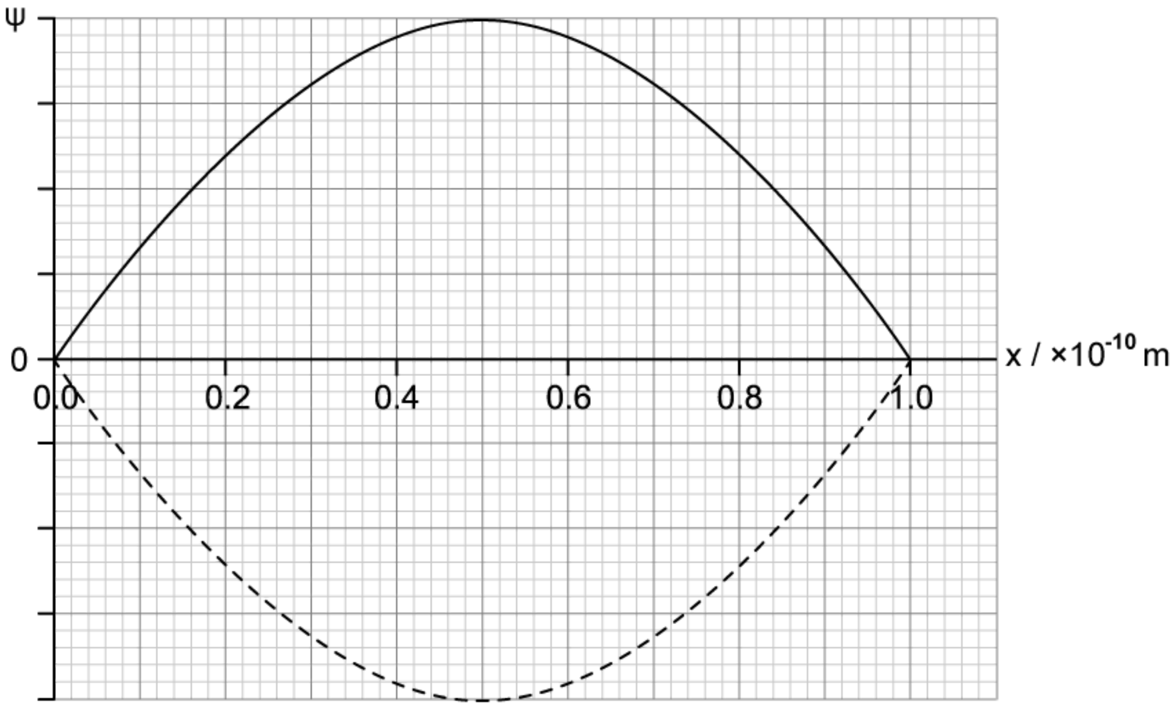
(3 marks)

(c) The wave function of Schrödinger's theory can be thought of as a generalisation of the de Broglie hypothesis.

Outline the relationship between the wave function of Schrödinger's theory and the de Broglie hypothesis.

(3 marks)

(d) The wave function ψ for an electron confined to length 1.0×10^{-10} m is a standing wave as shown.



(i) Explain why the most likely position near which the electron is discoverable is the centre of the box.

[2]

(ii) Calculate the momentum of the electron.

[2]

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(4 marks)

4 (a) One of the striking features of quantum theory is the ability of nature to convert matter into energy and vice versa.

Imagine an electron moving with kinetic energy E_k on a collision course with a positron moving in the opposite direction with the same kinetic energy. Following annihilation, two photons are produced.

Show that the wavelength λ of the two photons produced is given by the expression:

$$\lambda = \frac{2hc}{2m_e c^2 + m_e v^2}$$

where m_e is the mass of the electron.

(4 marks)

(b) Hence, show that the maximum wavelength of photons produced during this annihilation is approximately 2.4×10^{-12} m.

(2 marks)

(c) Show that the minimum wavelength of a photon that can produce an electron–positron pair is approximately 1.2×10^{-12} m.

(2 marks)

(d) Explain why the value for wavelength in part (c) is only an estimate and not an accurate result.

(2 marks)

5 (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.

[2]

(4 marks)

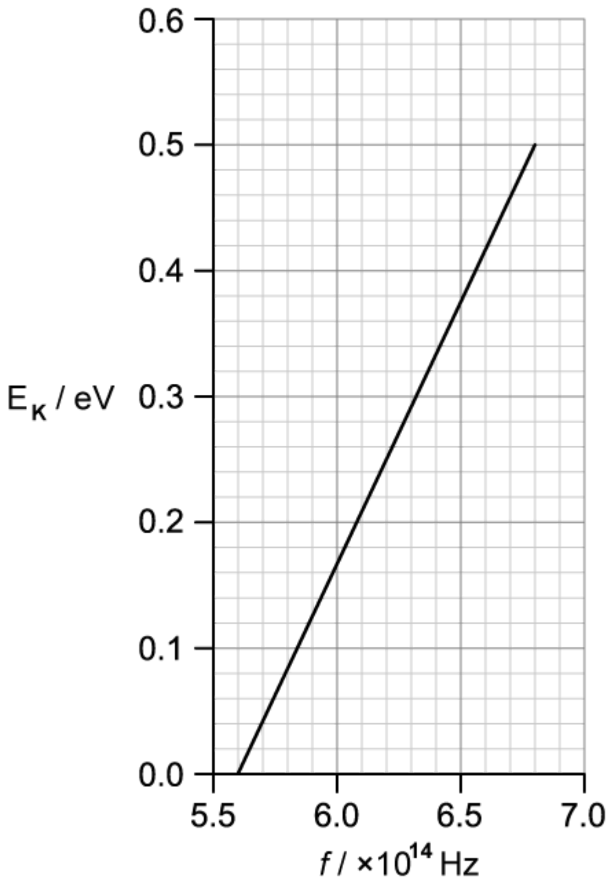
(b) The wavelength of light incident in part (a) is 450 nm and the work function of the metal is 2.0×10^{-19} J.

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)

Hard Questions

1 (a) An early form of the uncertainty principle was given by:

$$\Delta x \Delta p = h$$

Later, Heisenberg refined the expression by using the "reduced Planck constant" as a way to incorporate the quantisation of angular momentum into the principle. This constant is given by:

$$\hbar = \frac{h}{2\pi}$$

Derive the uncertainty principle of subatomic particles in terms of:

(i) Position and momentum.

[4]

(ii) Energy and time.

[2]

You may swap Planck's constant for the reduced Planck constant without justification.

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(6 marks)

(b) An alpha particle is confined within a nucleus of gold-197.

Using the uncertainty principle, estimate the kinetic energy, in MeV, of the alpha particle.

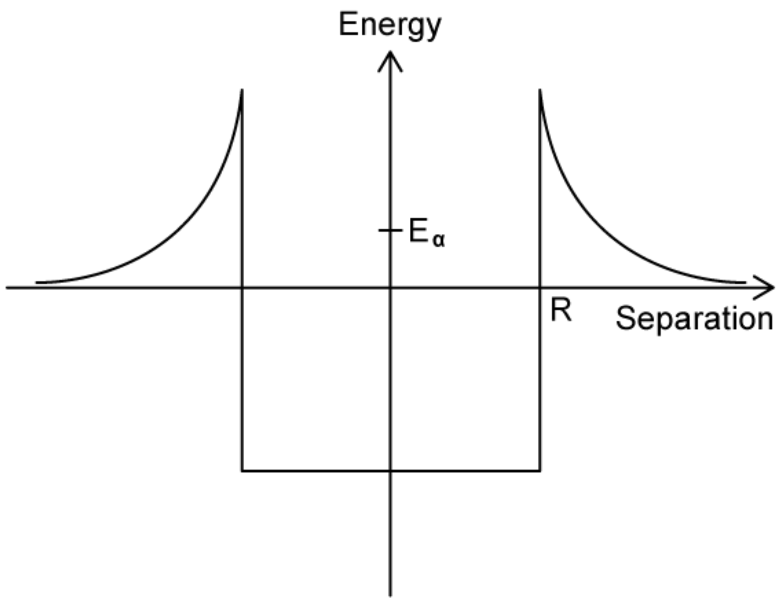
(4 marks)

(c) It is not possible to determine the exact location of an alpha particle confined within a nucleus.

Outline how this statement is consistent with the Schrödinger model of the atom.

(3 marks)

(d) An alpha particle confined in a nucleus with energy E_α can be considered to be in a potential well, as shown in the diagram. The nuclear radius is equal to R.



(i) Explain why classical mechanics dictates that the alpha particle should not be able to leave the nucleus.

[2]

(ii) Despite being forbidden by classical mechanics, alpha decay is observed in nature. By reference to the laws of quantum mechanics, explain how alpha decay is possible.

[2]

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(4 marks)

2 (a) (i) Outline how the de Broglie hypothesis explains the existence of a discrete set of wavefunctions for electrons confined in a box of length *L*.

[3]

(ii) Show that the kinetic energy of such an electron is given by:

$$E_K = \frac{n^2h^2}{8m_eL^2}$$

[3]

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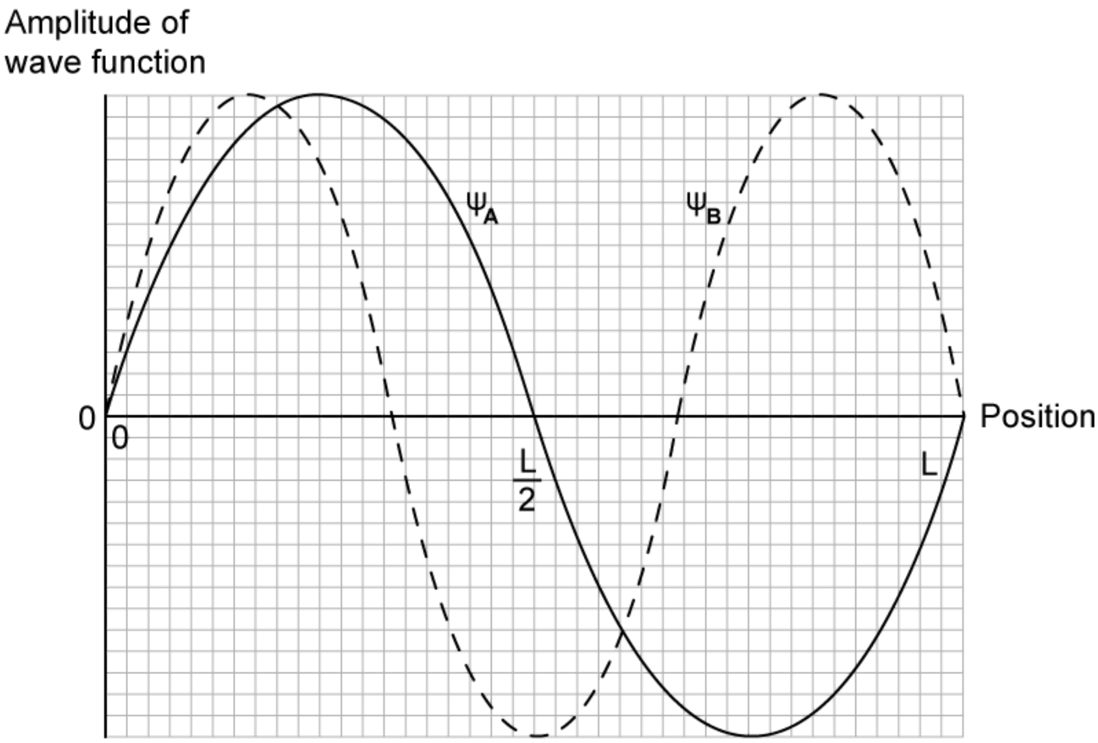
(6 marks)

(b) The diagram below shows the shape of two allowed wavefunctions Ψ_A and Ψ_B for an electron confined in a one-dimensional box of length L.



On the graph, sketch a possible wavefunction for the lowest energy state of the electron.

(2 marks)

(c) With reference to the de Broglie hypothesis, suggest which wavefunction, ψ_A or ψ_B, corresponds to the larger electron energy.

(3 marks)

(d) Predict and explain which wavefunction, ψ_A or ψ_B, indicates a larger probability of finding the electron near the middle of the box.

(3 marks)

3 (a) One of the striking features of quantum theory is the ability of nature to convert matter into energy and vice versa.

Imagine an electron moving with kinetic energy E_k on a collision course with a positron moving in the opposite direction with the same kinetic energy. Following annihilation, two photons are produced.

Show that the wavelength λ of the two photons produced is given by the expression:

$$\lambda = \frac{2hc}{2m_e c^2 + m_e v^2}$$

where m_e is the mass of the electron.

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(4 marks)

(b) Hence, show that the maximum wavelength of photons produced during this annihilation is approximately 2.4×10^{-12} m.

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(2 marks)

(c) Show that the minimum wavelength of a photon that can produce an electron–positron pair is approximately 1.2×10^{-12} m.

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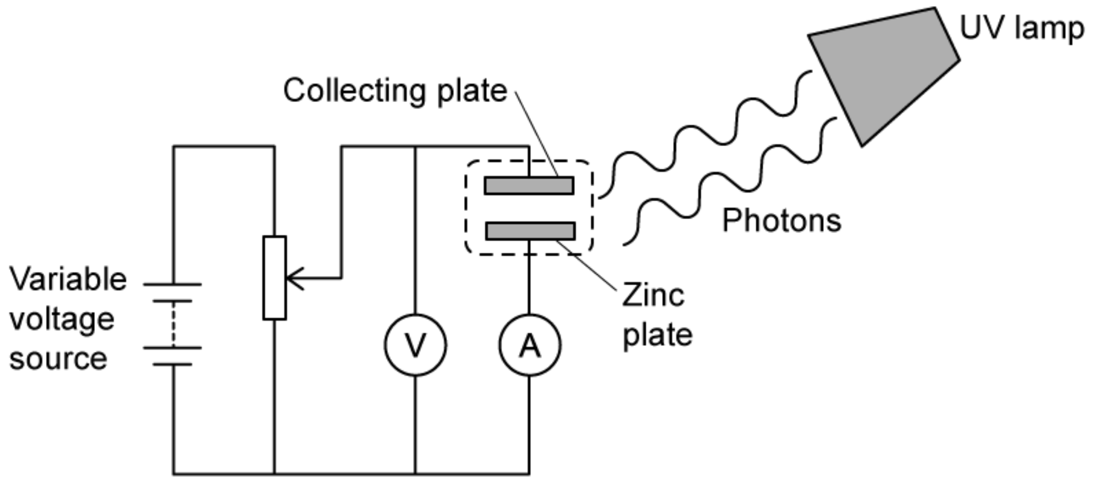
(2 marks)

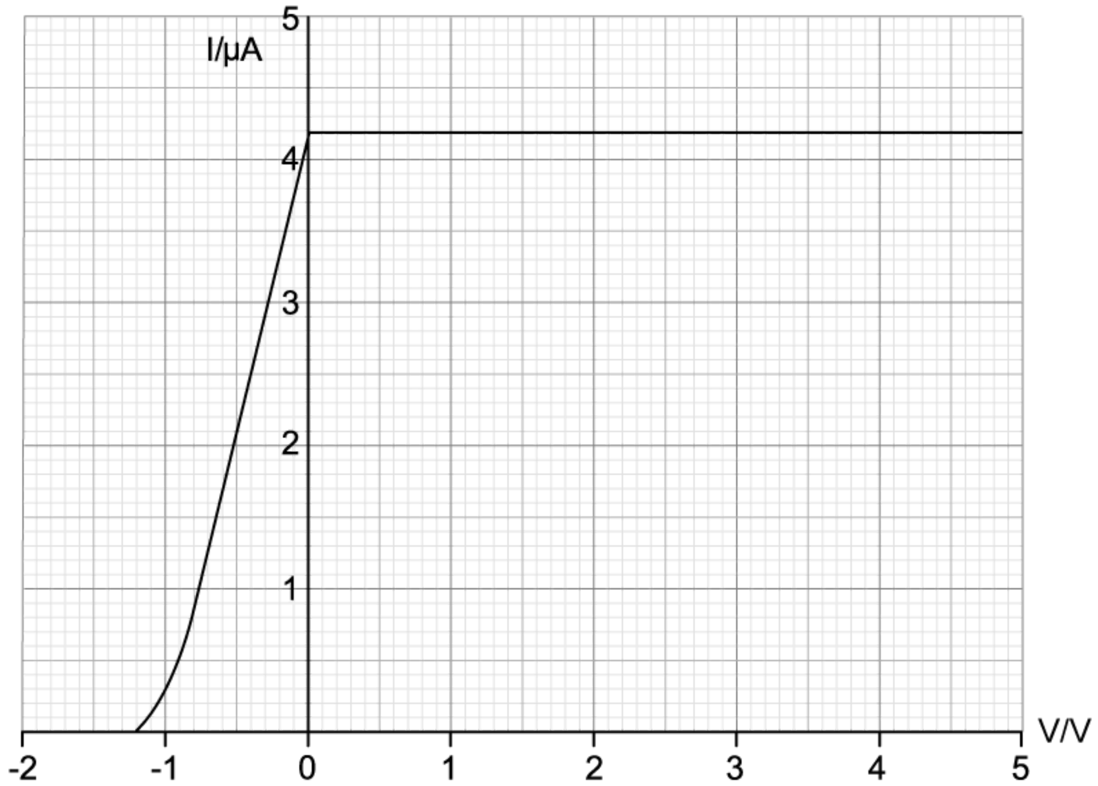
(d) Explain why the value for wavelength in part (c) is only an estimate and not an accurate result.

(2 marks)

4 (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)

(d) The zinc plate has dimensions of 2.5 mm × 2.5 mm. The intensity of the light incident on the surface is 3.5×10^{-6} W m^{-2}. On average, one electron is emitted for every 300 photons that are incident on the surface.

Determine the initial photocurrent leaving the metal surface.

(3 marks)

5 (a) Bohr modified the Rutherford model by introducing the condition:

$$mvr = n\frac{h}{2\pi}.$$

The total energy E_n of an electron in a stable orbit is given by:

$$E_n = -\frac{ke^2}{2r}$$

Where $k = \frac{1}{4\pi\varepsilon_0}$

(i) Discuss one issue posed by Rutherford's model and one issue solved by Bohr's modification.

[2]

(ii) Use Bohr's modification with the expression for total energy to derive the equation

$$E_n = \frac{K}{n^2}$$

[3]

(iii) State and explain what physical quantity is represented by the constant, *K*

[1]

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(6 marks)

(b) In 1908, the physicist Friedrich Paschen first observed the photon emissions resulting from transitions from a level *n* to the level *n* = 3 of hydrogen and deduced their wavelengths were given by:

$$\lambda = \frac{An^2}{n^2 - 9}$$

where A is a constant.

Justify this formula on the basis of the Bohr theory for hydrogen and determine an expression for the constant *A*.

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(3 marks)

(c) The electron stays in the first excited state of hydrogen for a time interval of approximately $\Delta t = 1.0 \times 10^{-10}$ s.

Suggest, with relevant calculations, why the photons emitted in transitions from the first excited state of hydrogen to the ground state will have a small range of wavelengths.

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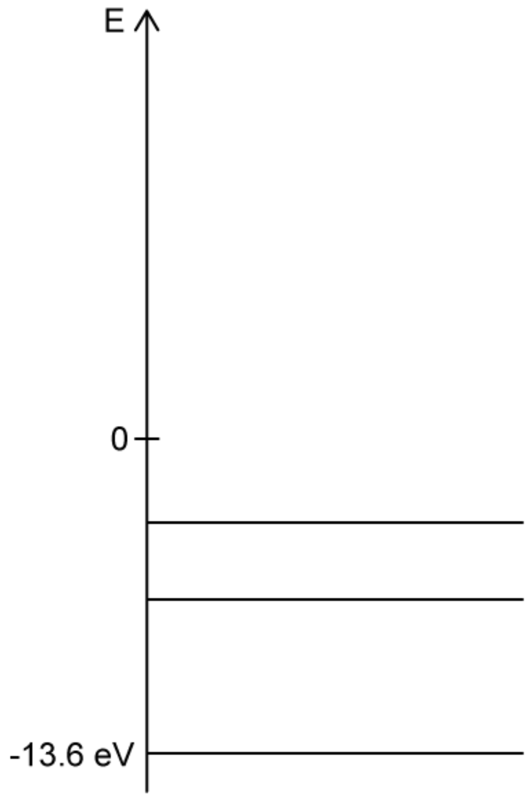
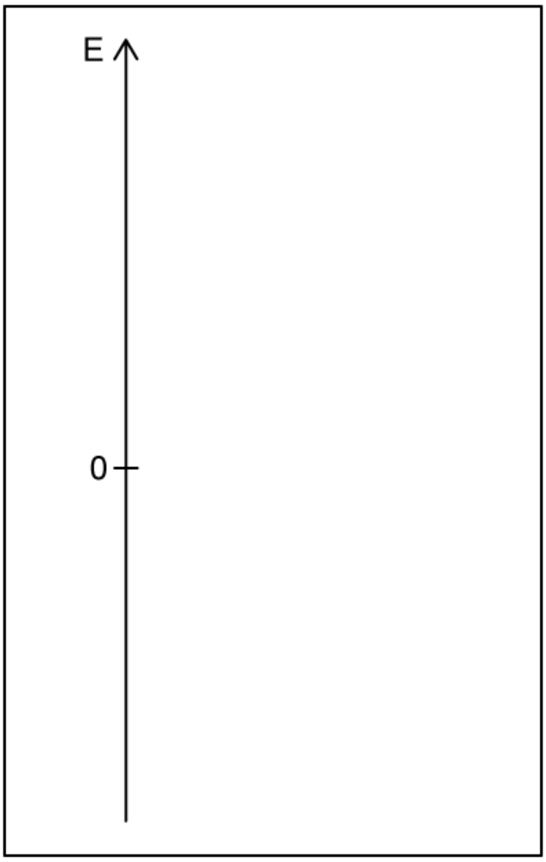
(4 marks)

(d) The three lowest energy levels for an electron in a hydrogen atom are shown.



Schrodinger's wave equation describes the boundary conditions of the three dimensions of an atom giving rise to both radial and angular allowed modes with discrete energy states. The wave equation describes the probability of finding an electron at a given point, for example, when an electron is confined in a box.



(i) Using the energy axis provided, draw the three lowest energy levels for an electron confined in a box. You do not have to put any numbers on the vertical axis.

[2]

(ii) Justify the reasoning behind the energy levels you have drawn.

[4]

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(6 marks)