12.1 The Interaction of Matter with Radiation

Question Paper

Course	DP IB Physics
Section	12. Quantum & Nuclear Physics (HL only)
Topic	12.1 The Interaction of Matter with Radiation
Difficulty	Hard

Time allowed: 90

Score: /75

Percentage: /100

Question 1a

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:

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

(a)
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.

[6 marks]

Question 1b

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

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

[4]

[4 marks]

Question 1c

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

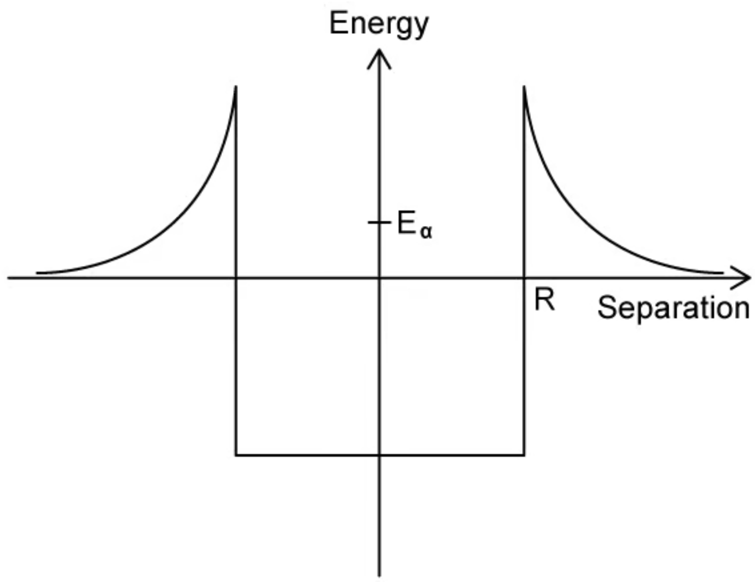
(c)
Outline how this statement is consistent with the Schrödinger model of the atom.

[3]

[3 marks]

Question 1d

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.



(d)

(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]

[4 marks]

Question 2a

(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:

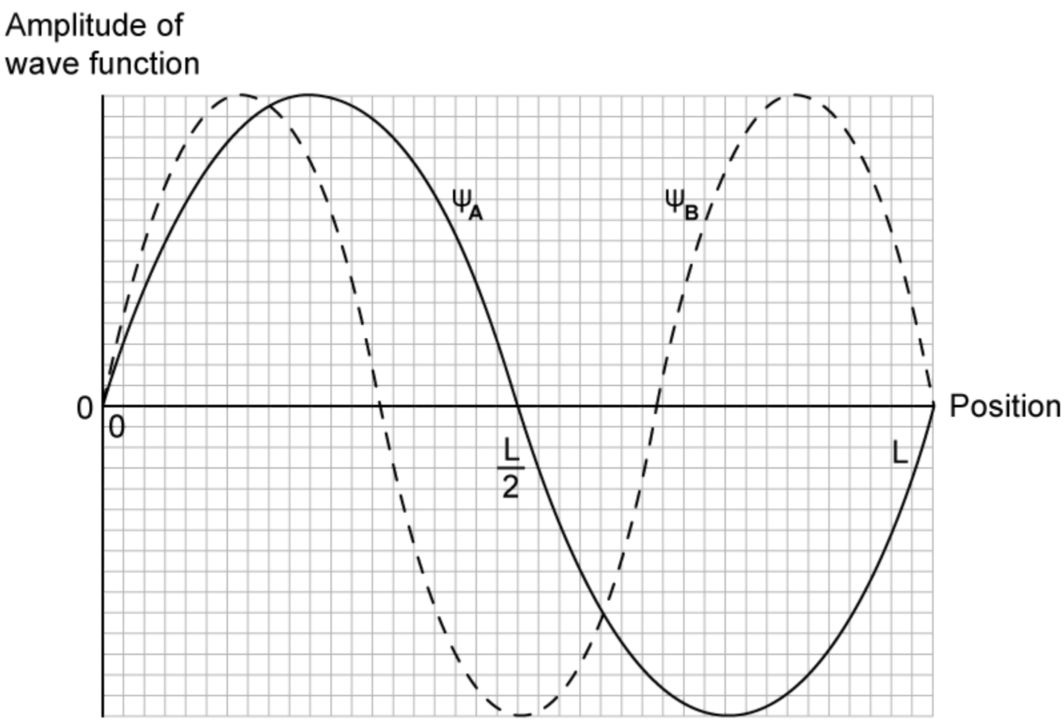
$$E_K = \frac{n^2 h^2}{8 m_e L^2}$$

[3]

[6 marks]

Question 2b

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.



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

[2]

[2 marks]

Question 2c

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

[3]

[3 marks]

Question 2d

(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]

[3 marks]

Question 3a

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.

(a)
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]

[4 marks]

Question 3b

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

[2]

[2 marks]

Question 3c

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

[2]

[2 marks]

Question 3d

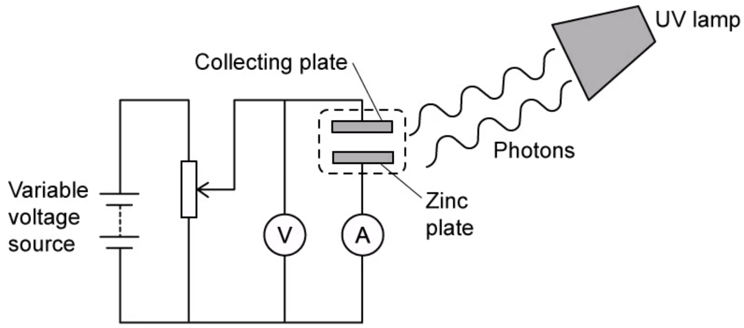
(d)
Explain why the value for wavelength in part (c) is only an estimate and not an accurate result.

[2]

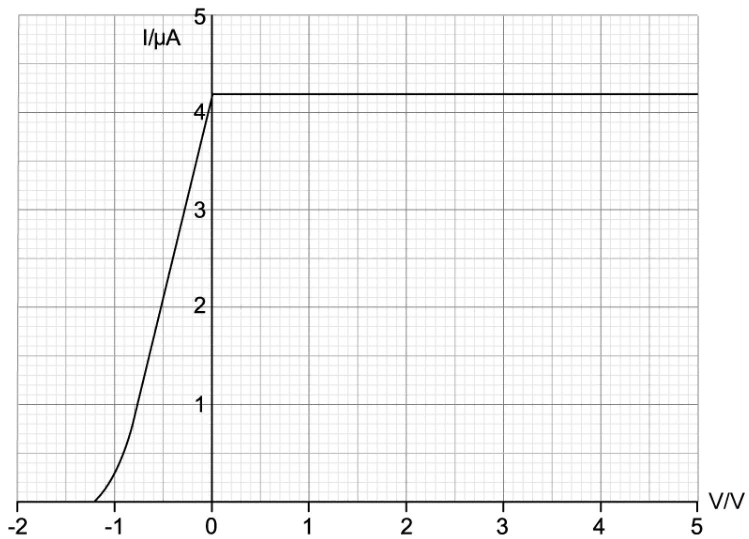
[2 marks]

Question 4a

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.



(a)

(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]

Question 4b

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

(b)

(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]

Question 4c

The work function of zinc is 3.74 eV.

(c)
Determine the wavelength of the ultraviolet light incident on the zinc plate.

[4]

[4 marks]

Question 4d

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.

(d)
Determine the initial photocurrent leaving the metal surface.

[3]

[3 marks]

Question 5a

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

(a)

(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]

[6 marks]

Question 5b

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.

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

[3]

[3 marks]

Question 5c

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

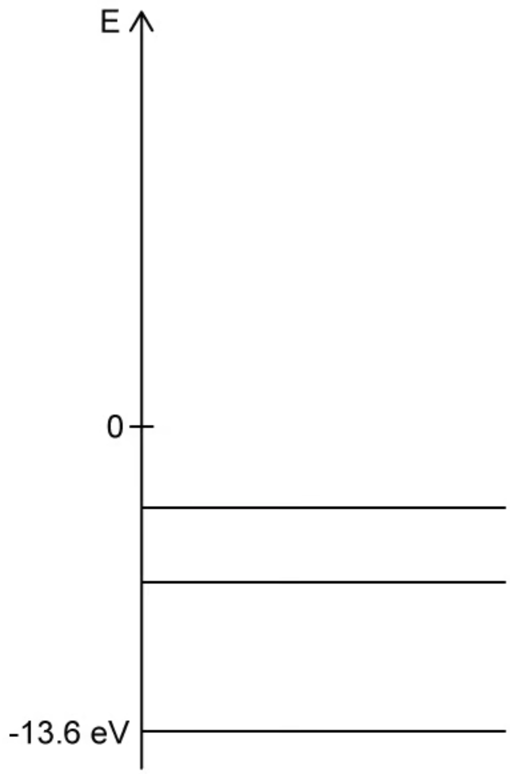
(c)
Suggest, with relevant calculations, why the photons emitted in transitions from the first excited state of hydrogen to the ground state will have a small range of wavelengths.

[4]

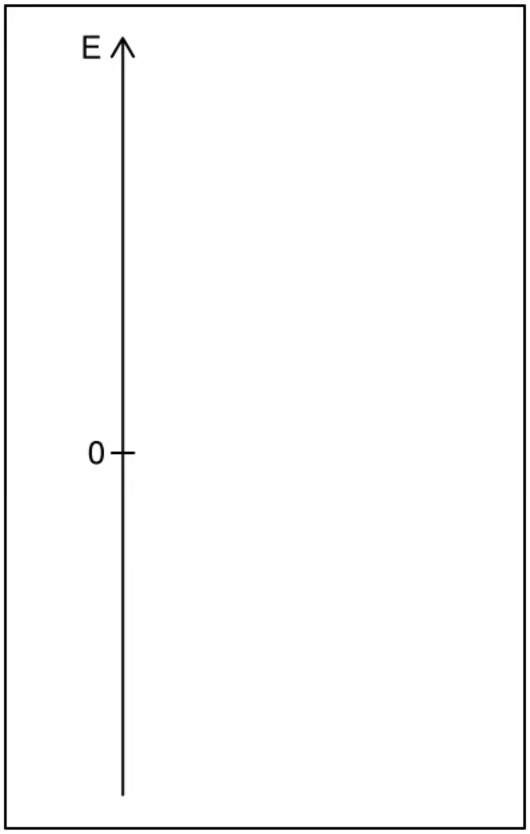
[4 marks]

Question 5d

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.



(d)

(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]

[6 marks]