Name: ____

Quantum

Date:

Time:

Total marks available:

Total marks achieved: ______

Questions

Q1.

In the 1920s Louis de Broglie proposed that an electron could behave as a wave.

Calculate the wavelength of an electron that is travelling at a speed of $2.2 \times 10^7 ms^{-1}$.

(3)

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Wavelength = ...

(Total for question = 3 marks)

Q2.

The electron in a hydrogen atom can be described by a stationary wave which is confined within the atom. This means that the de Broglie wavelength associated with it must be similar to the size of the atom which is of the order of 10^{-10} m.

(a) (i) Calculate the speed of an electron whose de Broglie wavelength is 1.00×10^{-10} m.

(3)

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Speed = ...

(ii) Calculate the kinetic energy of this electron in electronvolts.

(3)

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Kinetic energy = ... eV

(b) When β radiation was first discovered, it was suggested that there were electrons in the atomic nucleus, but it was soon realised that this was impossible because the energy of such an electron would be too great.

Suggest why an electron confined within a nucleus would have a much greater energy than the energy calculated in (a)(ii).

(2)

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(Total for question = 8 marks)

Q3.

(a) State what is meant by the de Broglie wavelength.

(2)

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(b) An electron is accelerated from rest, in a vacuum, through a potential difference of 500 V.

(i) Show that the final momentum of the electron is about 1×10^{-23} N s.

(3)

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(ii) Calculate the de Broglie wavelength for this electron.

(2)

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de Broglie wavelength = ...

(Total for question = 7 marks)

Q4.

In the 19th century experiments with magnetic and electric field deflections were used to determine the charge to mass ratio of electrons.
Later experiments showed the diffraction of electrons as they passed through thin metal foils.
Deduce what these experiments tell us about electrons.

(3)

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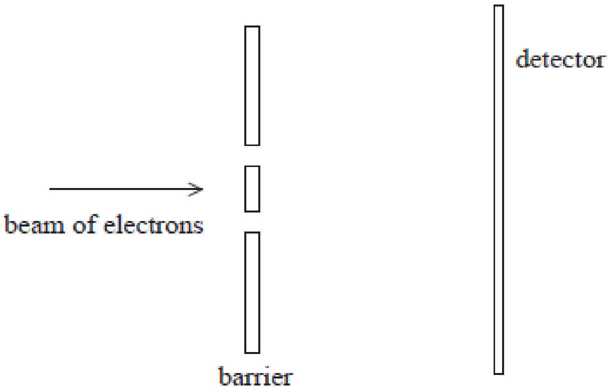
(Total for question = 3 marks)

Q5.

In 1965, Richard Feynman proposed a double slit experiment to investigate the wave properties of electrons.

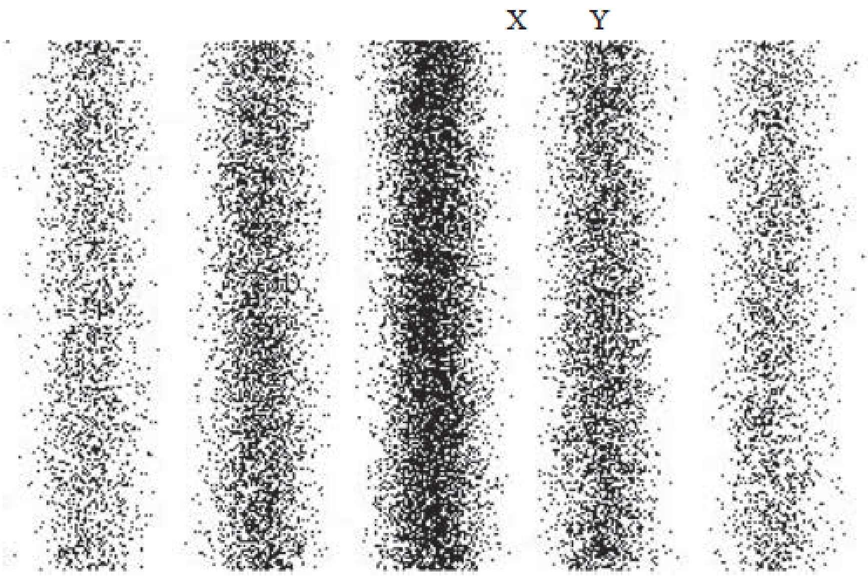
The experiment was later carried out using the arrangement shown.



A beam of electrons was directed at a barrier with two slits.

The detector recorded the positions where electrons arrived after passing through the slits.

The following pattern was obtained. Black dots represent points where electrons were detected. A band where electrons were not detected has been labelled X and a band where electrons were detected has been labelled Y.



The path difference for electrons arriving at band X from the separate slits was 2.5×10^{-1} m. For electrons arriving at band Y the path difference was 5.0×10^{-1} m.

Explain why this pattern is observed when the electron energy is 9.6×10^{-1} J.

The electrons are travelling at non-relativistic speeds.

(6)

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(Total for question = 6 marks)

Q6.

Our understanding of the atom has developed over time, from early models in which atoms were considered to be hard incompressible spheres, through to the nuclear model of the atom and the ladder model in which electrons exist in a discrete number of allowed energy states.

* The model of atoms as hard incompressible spheres, moving rapidly and randomly, can be used to explain why gases exert a pressure.

Explain, using ideas of momentum, why the pressure exerted by a gas increases as the temperature of the gas increases.

(6)

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(Total for question = 6 marks)

Q7.

An electron beam is directed onto crystalline graphite. A fluorescent screen on the other side of the crystal shows the pattern in Figure 1. The brighter areas correspond to higher electron intensity.

The speed of the electrons is increased and the resulting pattern is shown in Figure 2.

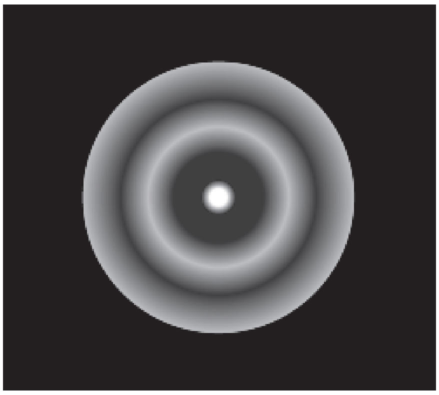

Figure 1

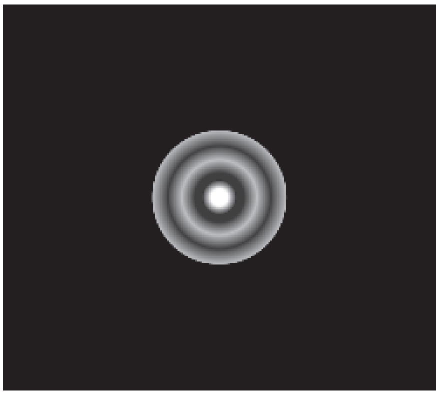

Figure 2

* Discuss the conclusions that can be drawn from this information about the behaviour of electrons and the structure of graphite.

(6)

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(Total for question = 6 marks)

Q8.

(a) Solar sails are a form of propulsion for spacecraft. The sail is made of a thin sheet of reflective material. When photons of light from the Sun reflect from the material a force is exerted on the sail. The photons reflect with a momentum equal to their initial momentum but in the opposite direction.

(i) Show that a single photon of frequency 1.5×10^{15} Hz has a momentum of about 3×10^{-27} N s.

(2)

....

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....

(ii) Hence determine the momentum transferred to the solar sail by this photon.

(1)

....

Momentum transferred = ...

(b) An alternative method of producing a momentum change is being investigated. Researchers have suggested that 'larger changes in momentum could be produced by directing laser light at graphene oxide'. Electrons are emitted from the graphene oxide surface, resulting in a force being exerted on the graphene oxide in the opposite direction.

A researcher has suggested that one possible mechanism for the emission of the electrons is the photoelectric effect.

(i) Show that the maximum velocity for a photoelectron emitted after absorption of a photon of light of frequency 1.5×10^{15} Hz is about 8×10^{5} m s^{-1}.

work function of graphene oxide = 6.7×10^{-19} J

(3)

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(ii) Hence calculate the momentum of the photoelectron.

(2)

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Momentum of photoelectron = ...

(c) Explain whether the suggestion in (b) that 'larger changes in momentum could be produced by directing laser light at graphene oxide' is true.

(2)

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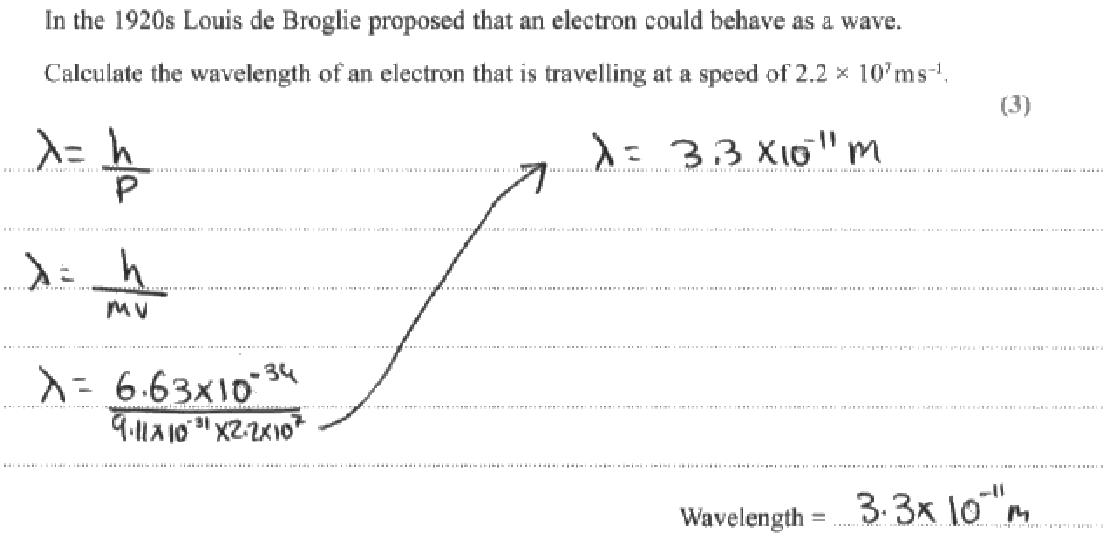
(Total for question = 10 marks)

Examiner's Report

Q1.

This was a three mark calculation involving the use of two equations, both given at the back of the paper. Using the de Broglie wavelength equation required a value for momentum which could be calculated using *p=mv* with the mass of an electron. This is where some candidates struggled as the mass of an electron was not given in the question, so they needed to realise that this was necessary and that the value is given at the back of the exam paper.

A small minority of candidates tried to use the equation *velocity = frequency × wavelength*, probably seeing that the question was about a wave, with a speed given and a wavelength required.



In the 1920s Louis de Broglie proposed that an electron could behave as a wave.

Calculate the wavelength of an electron that is travelling at a speed of $2.2 \times 10^7 \, \text{m s}^{-1}$.

(3)

$\lambda = \frac{h}{p}$

$\lambda = \frac{h}{mv}$

$\lambda = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 2.2 \times 10^7}$

$\lambda = 3.3 \times 10^{-11}$ m

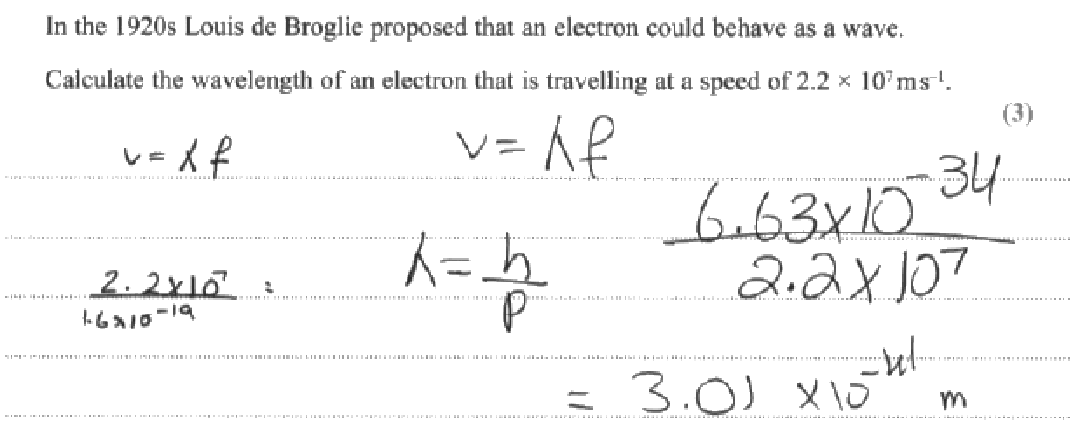
Wavelength = 3.3×10^{-11} m

Results Plus: Examiner Comments

This is a 3 mark answer. The candidate has combined the two equations before substituting the values. Full marks were also awarded if a candidate had calculated the momentum first and then substituted that value into the de Broglie equation.

Results Plus: Examiner Tip

In calculations where the mass of an electron is required don't forget that this is given in the list of data at the back of the exam paper.



In the 1920s Louis de Broglie proposed that an electron could behave as a wave.

Calculate the wavelength of an electron that is travelling at a speed of $2.2 \times 10^7 \, \text{m s}^{-1}$.

(3)

$v = \lambda f$ $v = \lambda f$

$\frac{2.2 \times 10^7}{1.6 \times 10^{-19}}$: $\lambda = \frac{h}{p}$ $\frac{6.63 \times 10^{-34}}{2.2 \times 10^7}$

$= 3.01 \times 10^{-41}$ m

Results Plus: Examiner Comments

This is an example of a common incorrect answer. This candidate did not know what to do with the value for *p* and has simply used the value for speed as given in the question.

They have tried dividing the speed by the charge on an electron but have not gone on to use this. Some candidates did use the charge on an electron instead of mass. Without a value for mass 0 marks could be scored.

Results Plus: Examiner Tip

There is an expectation that some constants are used even when not specified in the question.

Q2.

(a) Candidates scored very well, with the majority scoring full marks. When errors were made in the velocity calculation they were usually due to incorrect rearrangements of the formula at the start. The 'use of' mark at the beginning of most calculations is for substitution into a correct formula.

For weaker candidates, it is better to substitute into equations before they are rearranged. If they rearrange first (incorrectly) and then substitute, they will not receive the 'use of' mark. Examiners often saw $v = m\lambda/h$.

In the kinetic energy calculation, the common mistakes were either to fail to square the velocity if using KE = $mv^2/2$ or to multiply by e, instead of dividing.

12 The electron in a hydrogen atom can be described by a stationary wave which is confined within the atom. This means that the de Broglie wavelength associated with it must be similar to the size of the atom which is of the order of 10^{-10} m.

(a) (i) Calculate the speed of an electron whose de Broglie wavelength is 1.00×10^{-10} m.

(3)

$\lambda = \frac{h}{p}$

$p = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{1 \times 10^{-10}}$

$p = 6.63 \times 10^{-24}$ Ns

$p = mv$

$v = \frac{p}{m}$

$v = \frac{6.63 \times 10^{-24}}{9.11 \times 10^{-31}}$

$v = 7280000$

Speed = 7.28×10^{6} ms^{-1}

(ii) Calculate the kinetic energy of this electron in electronvolts.

(3)

$K.e. = \frac{1}{2} m v^2$

$= \frac{1}{2} \times 9.11 \times 10^{-31} \times (7.28 \times 10^{6})^2 = 2.4 \times 10^{-17}$ J

$\frac{2.4 \times 10^{-17}}{1.6 \times 10^{-19}} = 150.8$ eV

Kinetic energy = 151 eV

Results Plus: Examiner Comments

Responses like this were often seen: a perfect answer scoring all of the marks. 6 marks

12 The electron in a hydrogen atom can be described by a stationary wave which is confined within the atom. This means that the de Broglie wavelength associated with it must be similar to the size of the atom which is of the order of 10^{-10} m.

(a) (i) Calculate the speed of an electron whose de Broglie wavelength is 1.00×10^{-10} m.

$p = mv$

(3)

$\lambda = 1 \times 10^{-10}$ $\lambda = h/p$

$1.00 \times 10^{-10} = 6.63 \times 10^{-34} / p$

$p = 6.63 \times 10^{-44}$

$6.63 \times 10^{-44} = 9.11 \times 10^{-31} \times v$ $v = 7.28$

Speed = 7.28×10^{-14} ms^{-1}

(ii) Calculate the kinetic energy of this electron in electronvolts.

(3)

$Ke = \frac{1}{2}mv^2$ J → eV

$\times (3 \times 10^8)^2 \div eV$.

$Ke = \frac{1}{2} \times 9.11 \times (7.28 \times 10^{-14})^2$

$Ke = 2.41 \times 10^{-57} \times 3 \times 10^{8^2} \div 1.6 \times 10^{-19}$

Kinetic energy = 1.36×10^{-21} eV

Results Plus: Examiner Comments

(a)(i) This candidate has made an error with the powers of ten in the calculation of momentum. It scores the two method marks but not the last answer mark. (a)(i) The candidate could potentially score three marks here, using the value from (i), but in the energy calculation has missed the powers of ten off the mass of the electron. The candidate then multiplies by c^2, as well as dividing by e. The marks are independent, so this candidate scored one mark for dividing by e. 3 marks

12 The electron in a hydrogen atom can be described by a stationary wave which is confined within the atom. This means that the de Broglie wavelength associated with it must be similar to the size of the atom which is of the order of 10^{-10} m.

(a) (i) Calculate the speed of an electron whose de Broglie wavelength is 1.00×10^{-10} m.

(3)

$\lambda = h/p \quad \lambda = h/mv$

$mv = h/\lambda \quad v = \frac{6.63\times10^{-34}}{1.00\times10^{-10} \times 9.11\times10^{-31}}$

$v = \frac{h}{\lambda m} \quad = 7277716.795\ ms^{-1}$

Speed = $7.28\times10^{6}\ ms^{-1}$

(ii) Calculate the kinetic energy of this electron in electronvolts.

(3)

$E_k = \frac{1}{2}mv^2$

$= 0.5 \times 9.11\times10^{-31} \times 7.28\times10^{6}$

$= 3.315\times10^{-24}$ J

convert to eV → $3.315\times10^{-24} \div 1.6\times10^{-19}$

$= 2.07187\times10^{-5}$ eV

Kinetic energy = 2.07×10^{-5} eV

Results Plus: Examiner Comments

A common error in (ii). Despite writing $E_k = mv^2/2$ when substituting into the equation the candidate has forgotten to square the velocity. This scored 3 for (i) and 1 for (ii). 4 marks

Results Plus: Examiner Tip

Remember to learn the terms in equations.

(b) Since this question was about de Broglie, it was very surprising how few candidates thought to base their answer in terms of electron wavelength. The vast majority of candidates missed the point completely, and talked about attractive electrostatic forces between the protons and the electrons, the difficulties with the strong nuclear forces and many more inventive answers. Even those who did realise that it was about wavelengths, often scored only 1 mark, because they failed to say that the wavelength would have to be similar in size to the nucleus. It appeared that that was assumed, and candidates just commented on the wavelength being smaller.

(b) When β radiation was first discovered, it was suggested that there were electrons in the atomic nucleus, but it was soon realised that this was impossible because the energy of such an electron would be too great.

Suggest why an electron confined within a nucleus would have a much greater energy than the energy calculated in (a)(ii).

(2)

The de Broglie wavelength would have to be the same size as the nucleus, which is a lot smaller than the atom. A shorter wavelength means more energy. $E = hf$

Results Plus: Examiner Comments

A perfect answer that scores both marks. Very few of the candidates scored 2 marks and only a small number more scored 1 mark. 2 marks

This candidate does appreciate that the answer is to do with the associated de Broglie wavelength but fails to say that the wavelength is similar in size to the nucleus and so scored 1 mark.

(b) When β radiation was first discovered, it was suggested that there were electrons in the atomic nucleus, but it was soon realised that this was impossible because the energy of such an electron would be too great.

Suggest why an electron confined within a nucleus would have a much greater energy than the energy calculated in (a)(ii).

(2)

because if it was confined within a nucleus it would have to have a much shorter de broglie wavelengh and $v = \frac{h}{\lambda m}$ the shorter the wavelength the greater the velocity ∴ the greater the E_k

Results Plus: Examiner Comments

Think about the context of the question: the clue was in (a) where the electron of hydrogen was talked about. 1 marks

(b) When β radiation was first discovered, it was suggested that there were electrons in the atomic nucleus, but it was soon realised that this was impossible because the energy of such an electron would be too great.

Suggest why an electron confined within a nucleus would have a much greater energy than the energy calculated in (a)(ii).

(2)

nucleus is positive and held because of strong nuclear force. The electron would be attracted to the positive centre because it is negatively charged

Results Plus: Examiner Comments

A very frequent answer that scored no marks. 0 marks

Q3.

(mean mark 4.7 max mark 7)

This was generally well answered with marks usually lost for the definition. The definition of the de Broglie wavelength has been asked before and we always use the same mark scheme for definitions so we expected them to say that it is the wavelength associated with a particle with a given momentum. This is because a stationary particle does not have an associated de Broglie wavelength. In the calculation some candidates rather than use $E_k = p^2 /2m$ decided to use the mass of the electron in $E_k = ½ mv^2$ to find v and then use $p=mv$ to calculate momentum. The danger of doing extra steps is the increased risk of making an arithmetic error. Also some candidates set their calculation up correctly but did not do the calculation to show the answer to one more decimal place as is required in a 'show that' calculation.

Q4.

This question uses the command word **deduce**, which requires candidates to draw a conclusion from the information provided. Hence it is vital that for MP3 to be awarded candidates bring the two pieces of evidence together to make a conclusion that refers to wave-particle duality.

This question was well answered, with most candidates giving a description of the conclusions of the two sets of experiments leading to a statement about wave particle duality. Some candidates did not make it explicit which set of experiments they were referring to, and some candidates focused on the detection of charge in the field deflection experiment and ignored the evidence that these provided for the particle nature of electrons.

A small number of candidates, in seeing the use of metal foil, went off at a tangent and described the Rutherford alpha particle experiment results.

In the 19th century experiments with magnetic and electric field deflections were used to determine the charge to mass ratio of electrons.
Later experiments showed the diffraction of electrons as they passed through thin metal foils.
Deduce what these experiments tell us about electrons.

(3)

• These experiments ~~s~~ show the wave-particle duality of electrons
• The first experiment shows the electrons acting a particle as magnetic fields and electric fields would have no effect on a wave.
• The second experiment shows the wave nature of electrons. This is because only waves will be diffracted when passing through a thin metal foil, ~~so~~ but particles wouldn't diffract.

Results Plus: Examiner Comments

Although the response refers to the first experiment and the second experiment it is clear from the order in which these experiments are mentioned that correct experiments are being referenced for each effect. Hence 3 marks can be given.

In the 19th century experiments with magnetic and electric field deflections were used to determine the charge to mass ratio of electrons.
Later experiments showed the diffraction of electrons as they passed through thin metal foils.
Deduce what these experiments tell us about electrons.

(3)

Most of the electrons passed through the metal foils, suggesting that most of the atom is just empty space. Some of the electrons were deflected less than 90°, suggesting that there was an overall charge, repelling them away. Few deflected greater than 90°, suggesting this charge is centred in a nucleus.

Results Plus: Examiner Comments

This response is referring to alpha-particle scattering rather than electron deflection and diffraction experiments, so no credit can be given.

Results Plus: Examiner Tip

Read the question carefully to ensure that you are giving an answer to the question being posed.

Q5.

The marks here were equally divided between a calculation, using the energy to calculate momentum and then the relationship between the de Broglie wavelength and momentum, and an explanation of the interference observed. Students very often only addressed one of these and therefore did not make the connection between the calculated wavelength and the observed effect.

Of those completing a calculation, many used the quoted wavelength to calculate the energy instead.

Of those explaining interference, some did so in general terms and did not clearly link X to destructive interference and Y to constructive interference. Others got path difference and phase difference confused, saying that the phase difference was half a wavelength, for example, rather than saying that the path difference was half a wavelength.

The path difference for electrons arriving at band X from the separate slits was 2.5×10^{-11} m. For electrons arriving at band Y the path difference was 5.0×10^{-11} m.

Explain why this pattern is observed when the electron energy is 9.6×10^{-17} J.

The electrons are travelling at non-relativistic speeds.

(6)

- As the electrons travel through the double slit they act as waves so superpose and interfere.
- If the path difference is a whole number of wavelengths, they are in phase so they ~~superpo~~ constructively interfere causing areas of maximum amplitude such as at Y. This suggests that ~~the~~ one wavelength is 5.0×10^{-11} m ~~and~~ a multiple of it for any areas of maxima
- If the path difference is $(n + \frac{1}{2})\lambda$, the waves are in antiphase so they destructively interfere causing areas of minimum amplitude such as at X. The ~~[illegible]~~ path difference was 2.5×10^{-11} m which is half a wavelength.

Results Plus: Examiner Comments

This answers the interference part correctly but doesn't include any calculation related to the wavelength (3 marks).

The path difference for electrons arriving at band X from the separate slits was 2.5×10^{-11} m. For electrons arriving at band Y the path difference was 5.0×10^{-11} m.

Explain why this pattern is observed when the electron energy is 9.6×10^{-17} J.

The electrons are travelling at non-relativistic speeds.

(6)

$E_k = \frac{1}{2}mv^2 \therefore \sqrt{\frac{2E}{m_e}} = v = 1.45 \times 10^7 \text{ ms}^{-1}$

$\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34}}{1.45 \times 10^7 \times 9.11 \times 10^{-31}} = 5 \times 10^{-11}$ m

These patterns are observed because the de Broglie wavelength equation can be used to find these patterns. This equation links the momentum of a particle with its wavelength and given the energy of the particle its wavelength must be 5×10^{-11} m as calculated. The reduction in path difference is due to the dispersement of electrons as they get further from the central maximum.

Results Plus: Examiner Comments

3 marks were awarded here for the calculations, but the written part does not explain the interference effect observed.

The path difference for electrons arriving at band X from the separate slits was 2.5×10^{-11} m.
For electrons arriving at band Y the path difference was 5.0×10^{-11} m.

Explain why this pattern is observed when the electron energy is 9.6×10^{-17} J.

The electrons are travelling at non-relativistic speeds.

(6)

when electron energy is 9.6×10^{-17}, $E_K = \frac{1}{2}mv^2$.

~~[illegible]~~

~~Since $\lambda = \frac{h}{p}$ and $v = f\lambda$~~

$v = \sqrt{\frac{2E_K}{m}}$, $v = \sqrt{\frac{2 \times 9.6 \times 10^{-17}}{9.11 \times 10^{-31}}}$

$v = 1.45 \times 10^7$ since $\lambda = \frac{h}{p}$, $\lambda = \frac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 1.45 \times 10^7}$

$\therefore \lambda = 5.0 \times 10^{-11}$ m.

at point X, the path difference of the two waves of electons is equal to half of the wavelength of the electrons. This means the waves will meet in antiphase & undergo destructive interference when they superpose. This leaves zero/minimum intensity at band X so no electrons are detected here.

At band Y, the electrons meet with a path difference equal to 1 wavelength so they undergo constructive interference when they superpose as they meet in phase. This leaves a high intensity at band Y.

Results Plus: Examiner Comments

The full 6 marks have been awarded to this response which includes a full, correct calculation and the required explanation of the interference effect.

Q6.

This question is an extended writing question which assesses the students' ability to show a coherent and logical structured answer with linkage and fully sustained reasoning. There are 6 indicative content points, for which a maximum of 4 marks can be awarded.There are two further marks available for appropriate linkage of ideas.

Although the physics theory has been examined many times in the Legacy specification, students' responses were often lacking in detail. Some students thought that the question was asking for a mathematical derivation of the pressure equation, and so limited the marks that they could be awarded for their response. Many students correctly stated that as the temperature increases the molecular velocity/kinetic energy increases, as does the momentum. Fewer said that the rate or frequency of collision (or even the time between collisions) with the container walls increases as a result. Some students talked about collisions, but did not make a reference to the container walls. This implied that the collisions could have been with each other, which would not have explained an increase of pressure. Some students talked about gas and didn't mention atoms or molecules at all. The idea that the rate of change of momentum is equal to the force was regularly expressed as an equation without the terms being specified. Similarly, pressure as force per unit area was frequently expressed as a formula without defining the terms.

Our understanding of the atom has developed over time, from early models in which atoms were considered to be hard incompressible spheres, through to the nuclear model of the atom and the ladder model in which electrons exist in a discrete number of allowed energy states.

The model of atoms as hard incompressible spheres, moving rapidly and randomly, can be used to explain why gases exert a pressure.

Explain, using ideas of momentum, why the pressure exerted by a gas increases as the temperature of the gas increases.

(6)

Pat. As temperature increases, the gas molecules gain more kinetic energy. As a result, the number of collisions with the wall of the sphere increases as well. The increased kinetic energy of the molecules leads them to have greater velocities and hence greater momenta. Since $F = \frac{\Delta p}{\Delta t}$ (rate of change of momentum), and since Δp increases and Δt decreases, the resultant force increases. We also know that $P = \frac{F}{A}$, where P = pressure, F = Force and A is surface Area. Since the surface area is constant and the resultant force increases, we can see that the pressure exerted by the gas increases.

Results Plus: Examiner Comments

In this response all indicative content points except point 3 are seen, although the clarity of expression is variable.5 indicative content points equates to a mark of 3 for the content. 2 linkage marks are available, although the clarity of the argument is such that only 1 linkage mark was actually given. Overall this gave a score of 4 marks.

Results Plus: Examiner Tip

Be specific and use technical terms wherever possible.

Our understanding of the atom has developed over time, from early models in which atoms were considered to be hard incompressible spheres, through to the nuclear model of the atom and the ladder model in which electrons exist in a discrete number of allowed energy states.

The model of atoms as hard incompressible spheres, moving rapidly and randomly, can be used to explain why gases exert a pressure.

Explain, using ideas of momentum, why the pressure exerted by a gas increases as the temperature of the gas increases.

(6)

As the temperature of a gas (in a fixed container of constant volume) increases, then the average kinetic energy per molecule (sphere of gas) increases. This means that the speed at which the molecules are moving inside of the container increases, and hence the rate of collisions of gas spheres with the sides/walls of the container increases. As the gas spheres have more kinetic energy, their momentum given by mass × velocity increases, and hence the momentum transferred to the walls of the container per collision increases (i.e impulse or Δp of walls increase). If the impulse transferred to the container walls increases, then, as I ∝ Force, then the force exerted on the sides and walls of the container by the molecules of gas increases, as force is the rate of change of momentum, and momentum transfer increases, so F increases. Finaly a pressure = $\frac{Force}{Area}$, for a container of fixed volume, Area is constant, and so if the force on the walls increases, then the pressure inside of the container increases. Collisions of gases with walls are elastic, motion of gases is random (Brownian motion) and volume of gases is negligible (easily compressed)

Results Plus: Examiner Comments

This is a good answer to the question. All 6 indicative content points are made, giving a mark of 4 for content. The logical flow of the argument is good enough for both linkage marks to be given.

Results Plus: Examiner Tip

Plan your answer to a question like this before you start to write. Planning your response will help you to write your answer out logically and with a minimum of repetition.

Q7.

This style of question is new to this specification and there will be one or two on each paper. Of the 6 marks available, 4 marks are awarded for the physics and 2 marks for the candidate's ability to show a coherent and logically structured answer with linkages and fully sustained reasoning.

Candidates of all abilities were able to gain marks in this written answer with most candidates scoring 3 marks.

Electron diffraction is new to the AS specification so it was encouraging to see that candidates had gained knowledge and understanding in this area.

An electron beam is directed onto crystalline graphite. A fluorescent screen on the other side of the crystal shows the pattern in Figure 1. The brighter areas correspond to higher electron intensity.

The speed of the electrons is increased and the resulting pattern is shown in Figure 2.

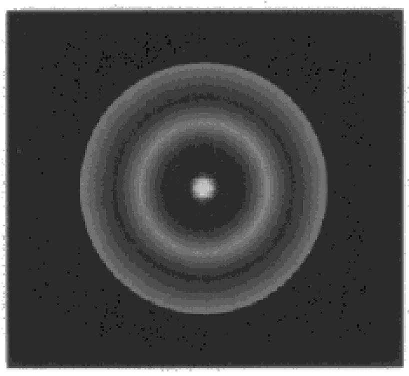


Figure 1

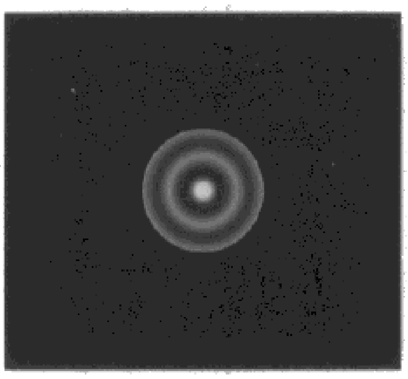


Figure 2

* Discuss the conclusions that can be drawn from this information about the behaviour of electrons and the structure of graphite.

(6)

In the diagrams it can be seen that when this experiment is performed electrons behave as waves and produce an interference pattern. While this does not mean that electrons are waves it shows that they exhibit wave-like properties.

Diffraction can only occur when the gap it occurs through is of a similar size to that which is being diffracted. From this we can conclude that the structure of crystalline graphite is such that the gaps between atoms is similar to the wavelength of the electron given by $\lambda = \frac{h}{p}$ – de broglies equation – when travelling at a certain speed.

Results Plus: Examiner Comments

In the first paragraph there are two physics points: recognising an interference pattern and that this demonstrates electrons exhibiting wave properties, which gets 2 marking marks. One linkage mark from the first paragraph is also awarded. A total of 3 marks.

In the second paragraph the candidate goes on to talk about the size of gaps in graphite being linked to the amount of diffraction. This was commonly seen. Whilst the de Broglie equation is given, it has not been linked to the speed and wavelength of electrons. Neither is there any mention of the pattern getting smaller as speed increases. No marks can be awarded in the second paragraph.

Results Plus: Examiner Tip

Quoting an equation in a written answer can be a useful way to justify the physics behind what you are saying. However, all terms in the equation must be defined.

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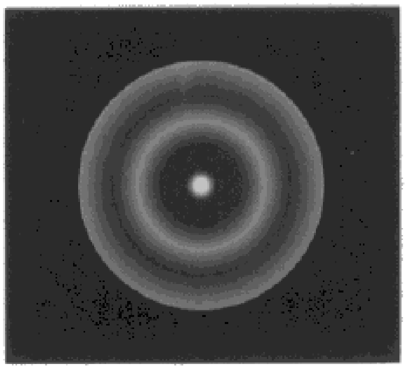

Figure 1

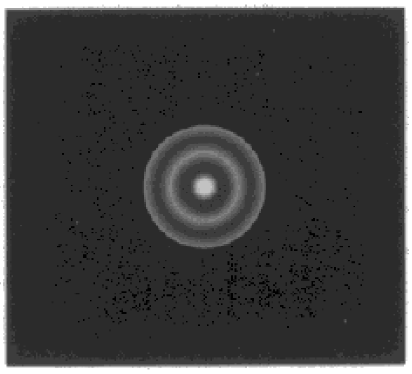

Figure 2

* Discuss the conclusions that can be drawn from this information about the behaviour of electrons and the structure of graphite.

(6)

The bright areas are caused by electron diffraction. Only waves can undergo diffraction which shows that electrons can exhibit wave-like properties. Higher electron speed causes the bright rings to become sharper and closer together which suggests that the de Brogile's wavelength of electrons decreases as speed increases because Smaller wavelength diffract less and therefore lead to a narrower pattern. $\lambda = \frac{h}{p} = \frac{h}{mv}$ so a larger value for v results in a smaller wavelength. For diffraction to occur the electrons must go through a gap which suggests that there must be spaces between the carbon atoms in graphite whose width is similar to the de Brogile's wavelength of the beam of electrons.

Results Plus: Examiner Comments

This answer scores a total of 5. There are 5 physics points in the answer for which 3 marks are gained, plus 2 linkage marks.

The only physics point missing is the reference to angles and wavelength, the 4th Physics point on the mark scheme. This point was rarely seen.

Q8.

The context of solar sails is most probably unfamiliar to most candidates; many candidates managed to successfully score marks, most commonly on the second half of the question that dealt with the photoelectric effect over the first half that covered the de Broglie equation. Only the most able candidates managed to pull together the two ideas and make a comparison of the two methods in part (c). However, 75 % of candidates scored at least 1 mark on this question and, with the exception of those scoring full marks, all other marks were equally distributed between the candidates so this question differentiated well across all abilities (of E grade and above).

(a) (i) Those candidates that did not appreciate that the wavelength had to be determined in order to use the de Broglie equation for the momentum of a photon tended to go down some incorrect routes that mainly involved trying to calculate the 'mass' of a photon to then obtain its momentum. Therefore, less able candidates tended to fair less well in this half of the question.

(a) (ii) Surprisingly few candidates managed to pick up a mark here. Candidates most commonly re-stated their answer to part (i), while others re-wrote it with a negative sign.

(b) (i) This multi-step calculation was answered less successfully than expected. The substitutions into the photoelectric equations were nearly always correct when attempted for the energy of the incident light and work function but not all managed to substitute for the kinetic energy, or used an incorrect mass. Those that did manage to substitute correctly sometimes went on to have difficulty to re-arrange the equation and make 'v' the subject of the equation. However, in such cases 2 of the 3 marks could still be scored.

(b) (ii) This calculation was often completed with success although quite a few candidates did not score the final mark due to a unit missing.

(c) As mentioned above, candidates found this to be challenging as many had just worked through the values involved in the question without much consideration of the context. In this final part of the question candidates were asked to explain if larger changes in momentum could be produced using laser light (i.e. the photoelectric effect) compared to reflected light from the sun. Many candidates attempted to explain why the statement was true as opposed to whether it was true. MP2 was the most frequently awarded marking point for identifying that the ejection of the photoelectron produced a larger change of momentum than for the reflection of the photon.

This response scored (a)(i) 2 marks, (a)(ii) 0 marks, (b)(i) 3 marks, (b)(ii) 2 marks and (c) 1 mark.

(a) Solar sails are a form of propulsion for spacecraft. The sail is made of a thin sheet of reflective material. When photons of light from the Sun reflect from the material a force is exerted on the sail. The photons reflect with a momentum equal to their initial momentum but in the opposite direction.

(i) Show that a single photon of frequency 1.5×10^{15} Hz has a momentum of about 3×10^{-27} N s.

(2)

$v = f\lambda$

$\lambda = \frac{v}{f} = \frac{(3 \times 10^{8})}{(1.5 \times 10^{15})} = 2 \times 10^{-7}$ m

$\lambda = \frac{h}{p}$

$p = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{2 \times 10^{-7}} = 3.315 \times 10^{-27}$ Ns

(ii) Hence determine the momentum transferred to the solar sail by this photon.

(1)

Momentum transferred = -3.315×10^{-27} Ns

(b) An alternative method of producing a momentum change is being investigated. Researchers have suggested that 'larger changes in momentum could be produced by directing laser light at graphene oxide'. Electrons are emitted from the graphene oxide surface, resulting in a force being exerted on the graphene oxide in the opposite direction.

A researcher has suggested that one possible mechanism for the emission of the electrons is the photoelectric effect.

(i) Show that the maximum velocity for a photoelectron emitted after absorption of a photon of light of frequency 1.5×10^{15} Hz is about 8×10^{5} m s^{-1}.

work function of graphene oxide = 6.7×10^{-19} J

(3)

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

$(6.63 \times 10^{-34}) \times (1.5 \times 10^{15}) = 6.7 \times 10^{-19} + \frac{1}{2} \times (9.11 \times 10^{-31}) v^2$

$-6.7 \times 10^{-19} = \frac{1}{2} \times (9.11 \times 10^{-31}) \times v^2$

$v = 844040.2548$ ms^{-1}

(ii) Hence calculate the momentum of the photoelectron.

(2)

$p = mv = (9.11 \times 10^{-31}) \times 844040.2548$

$= 7.6892... \times 10^{-25}$

Momentum of photoelectron = 7.68×10^{-25} kgms^{-1}

(c) Explain whether the suggestion in (b) that 'larger changes in momentum could be produced by directing laser light at graphene oxide' is true.

(2)

momentum of photoelectron emitted after absorption of a photon is higher than the momentum of a single photon, so suggestion is true

Results Plus: Examiner Comments

(a)(i) The wave equation was used to determine the wavelength of the light from the sun. The wavelength was then used in the de Broglie equation to calculate the momentum of the light. The final answer was quoted to at least one more significant figure than the 'show that' value giving 2 marks.

(a)(ii) As mentioned earlier, (ii) was not answered as well and this candidate has just placed a '−' in front of their momentum from part (i) which does not demonstrate the change in momentum, just the momentum after the reflection from the sail.

(b) (i) Correct substitution of all variables into the photoelectric equation and re-arranged successfully to give the velocity to at least 1 more significant figure than the 'show that' value of 8×10^5 m s^{-1}.

(b)(ii) $p = mv$ used successfully to give the correct momentum with unit, so 2 marks.

(c) MP2 awarded for a correct comparison of the change in momentum produced from a photoelectron and a single photon.

This response scored (a)(i) 2, (a)(ii) 1, (b)(i) 1, (b)(ii) 0 and (c) 0 marks.

(a) Solar sails are a form of propulsion for spacecraft. The sail is made of a thin sheet of reflective material. When photons of light from the Sun reflect from the material a force is exerted on the sail. The photons reflect with a momentum equal to their initial momentum but in the opposite direction.

(i) Show that a single photon of frequency 1.5×10^{15} Hz has a momentum of about 3×10^{-27} N s.

(2)

~~f = 1.5×10^15~~ v = f   3×10^8 = fλ -> λ = 2×10^-7

~~P = mv~~ λ = h/p -> 2×10^-7 = 6.63×10^-34

P = 6.63×10^-34 / 2×10^-7   P = 3.315 ×10^-27

(ii) Hence determine the momentum transferred to the solar sail by this photon.

(1)

3.315 ×10^-27 × 2 = 6.63×10^-27

Momentum transferred = 6.63×10^-27

(b) An alternative method of producing a momentum change is being investigated. Researchers have suggested that 'larger changes in momentum could be produced by directing laser light at graphene oxide'. Electrons are emitted from the graphene oxide surface, resulting in a force being exerted on the graphene oxide in the opposite direction.

A researcher has suggested that one possible mechanism for the emission of the electrons is the photoelectric effect.

(i) Show that the maximum velocity for a photoelectron emitted after absorption of a photon of light of frequency 1.5×10^{15} Hz is about 8×10^{5} m s^{-1}.

work function of graphene oxide = 6.7×10^{-19} J

(3)

hf = ϕ + ½mv²

6.63×10^-34 × 1.5×10^15 = 6.7×10^-19 + ~~½(1.6×10~~ ½mv²

1.484×10^-5 = ½mv²

v² = 1.484×10^-5 × 2 / 1.6×10^-19 = 1.855×10^14 -> v = 1.36×10^7

(ii) Hence calculate the momentum of the photoelectron.

(2)

$P = mV = 1.6 \times 10^{-19} \times 1.36 \times 10^{7} = 2.18 \times 10^{-12}$

Momentum of photoelectron = 2.18×10^{-12}

(c) Explain whether the suggestion in (b) that 'larger changes in momentum could be produced by directing laser light at graphene oxide' is true.

(2)

If the light has a higher frequency, the kinetic energy would be higher, therefor the photelectron would travel faster. As the photoelectron is travelling faster and has a constant mass, the momentum must increase

Results Plus: Examiner Comments

(a)(i) Wavelength and then momentum correctly calculated and answered to more than 1 significant figure.

(a)(ii) Value for the momentum from part (a)(i) doubled to give the correct change in momentum so 1 mark.

(b)(i) Line 2 shows the energy of the incident light and the work function correctly substituted into the photoelectric equation. The equation has not been correctly re-arranged and the charge of an electron has been substituted in for its mass so no further credit.

(b)(ii) Again, the charge of the electron rather than its mass has been used in the momentum equation so no marks here.

(c) This is more of a 'why?' than a 'which?' explanation which did not score any marks.