1 When light of a certain frequency is shone on a particular metal surface, electrons are emitted with a range of kinetic energies.

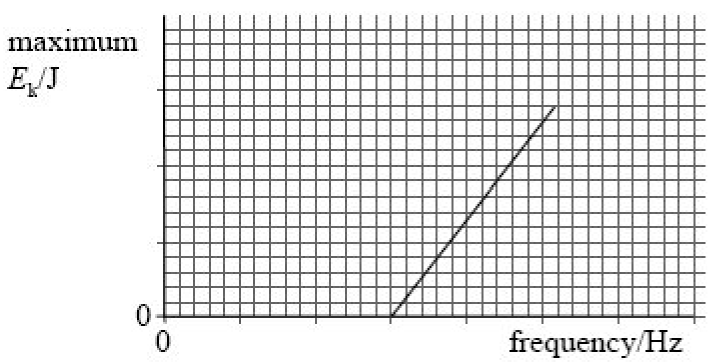
(a) Explain

- in terms of photons why electrons are released from the metal surface, and
- why the kinetic energy of the emitted electrons varies upto a maximum value.

The quality of your written communication will be assessed in this question.

(6)

(b) The graph below shows how the maximum kinetic energy of the electrons varies with the frequency of the light shining on the metal surface.



(i) On the graph mark the *threshold frequency* and label it f_0.

(1)

(ii) On the graph draw a line for a metal which has a higher threshold frequency.

(2)

(iii) State what is represented by the gradient of the graph.

____

(1)

(c) The threshold frequency of a particular metal surface is 5.6×10^{14} Hz. Calculate the maximum kinetic energy of emitted electrons if the frequency of the light striking the metal surface is double the threshold frequency.

answer = ____________________ J

(3)

(Total 13 marks)

2 (a) A particular photocell is designed to emit electrons when visible light is incident on its cathode. When yellow light of wavelength 570 nm is incident on the cathode the electrons are emitted with almost zero kinetic energy.

speed of electromagnetic radiation in a vacuum	=	3.0×10^{8} m s^{-1}
the Planck constant	=	6.6×10^{-34} J s
charge on electron	=	-1.6×10^{-19} C

(i) Show that the threshold frequency of the cathode material is about 5×10^{14} Hz.

(2)

(ii) Calculate the work function of the cathode material.

(2)

(b) Ultra-violet radiation of photon energy 4.7×10^{-19} J and of the same intensity as the visible light in part (a) is now incident on the cathode.

(i) Calculate the maximum velocity of the emitted electrons.
mass of electron = 9.1×10^{-31} kg.

(4)

(ii) State and explain the effect on the number of electrons emitted per second resulting from this change in the photon energy of the incident radiation.

____

____

____

____

(2)
(Total 10 marks)

3

The diagram represents some of the energy levels of an isolated atom. An electron with a kinetic energy of 2.0×10^{-18} J makes an inelastic collision with an atom in the ground state.

(a) Calculate the speed of the electron just before the collision.

____

____

____

(2)

(b) (i) Show that the electron can excite the atom to level 2.

(ii) Calculate the wavelength of the radiation that will result when an atom in level 2 falls to level 1 and state the region of the spectrum to which this radiation belongs.

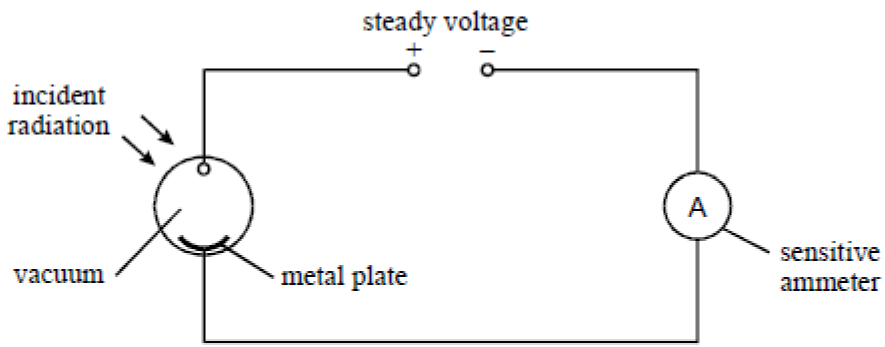
(6)

(c) Calculate the minimum potential difference through which an electron must be accelerated from rest in order to be able to ionise an atom in its ground state with the above energy level structure.

(2)

(Total 10 marks)

4 (a) Discovery of the photoelectric effect was largely responsible for the development of the theory that electromagnetic radiation can behave as a particle or as a wave under different circumstances. The diagram below shows an experimental arrangement used to demonstrate aspects of the photoelectric effect. When photoelectrons are emitted the ammeter registers a current.



(i) The metal plate is illuminated with radiation but does not emit photoelectrons. The intensity of the radiation is increased. State and explain what effect this increase in intensity has.

___

___

___

(2)

(ii) The metal plate is illuminated with radiation such that photoelectrons are emitted. The intensity of the radiation is increased. State and explain what effect this increase in intensity has.

___

___

___

___

(2)

(iii) The metal plate is illuminated with radiation such that photoelectrons are emitted. Air is now allowed to enter the enclosure. State and explain what effect allowing air into the enclosure has.

___

___

___

(2)

(b) (i) Show that the de Broglie wavelength of an electron travelling at $0.15c$ should be approximately 1.6×10^{-11} m.

the Plank constant, $h = 6.6 \times 10^{-34}$ J s
the speed of electromagnetic waves in a vacuum, $c = 3.0 \times 10^{8}$ m s^{-1}
the mass of an electron, $m_e = 9.1 \times 10^{-31}$ kg

(2)

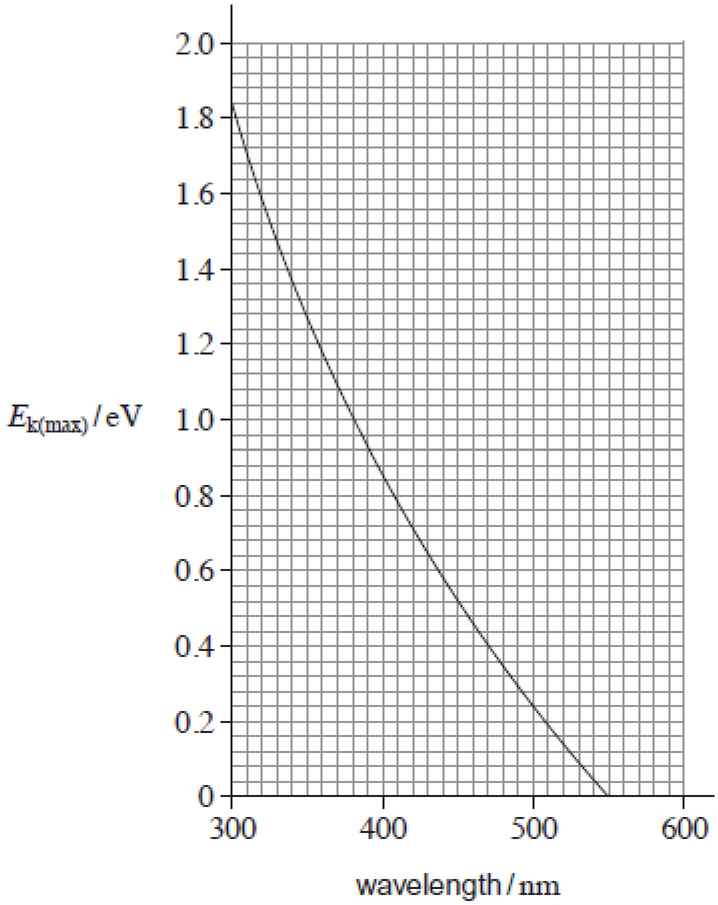
(ii) Suggest a suitable material to give an observable diffraction pattern with electrons. Explain your choice.

___

___

(2)
(Total 10 marks)

5 The maximum kinetic energy, $E_{k(max)}$, of photoelectrons varies with the wavelength of electromagnetic radiation incident on a metal surface.
This variation is shown in the graph.



(a) (i) Define the term work function.

____

____

____

(2)

(ii) Show that the work function of the metal is approximately 4×10^{-19} J.

Use data from the graph in your calculation.

(3)

(b) Monochromatic radiation is incident on the metal surface.
Photoelectrons are ejected with a maximum speed of 4.6×10^5 m s^{-1}.

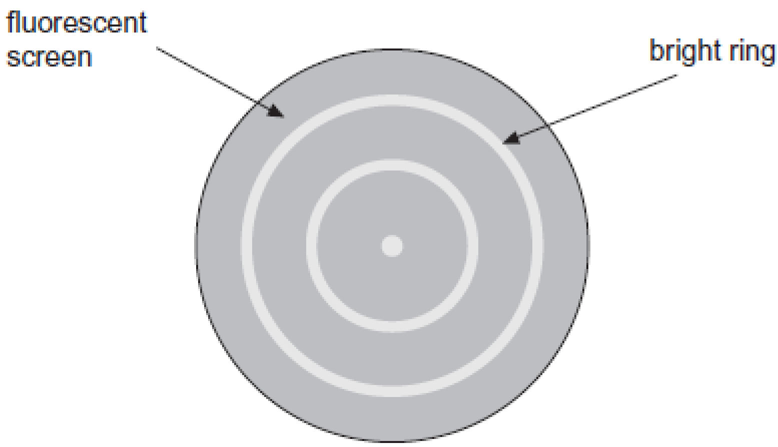
Determine the wavelength of the incident radiation.

wavelength ____________________ m

(3)

(Total 8 marks)

6 In an electron diffraction tube, high speed electrons are produced by an electron gun at one end of the tube. The electrons are incident on a thin slice of a polycrystalline material.
The diagram shows the pattern of bright rings that is formed on the fluorescent screen at the other end of the tube.



(a) Explain how the production of bright rings suggests that the electrons behave like waves.

____

____

(1)

(b) The electrons in the tube have a velocity of 3.5×10^7 m s^{-1}.

Calculate the de Broglie wavelength of the electrons.

de Broglie wavelength ____________________ m

(2)

(Total 3 marks)

7 Sodium metal has a work function of 2.28 eV. An atom of sodium has an ionisation energy of 5.15 eV.

(a) (i) State what is meant by work function.

____

____

(2)

(ii) State what is meant by ionisation energy.

____

____

(2)

(b) Show that the minimum frequency of electromagnetic radiation needed for a photon to ionise an atom of sodium is about 1.2×10^{15} Hz.

(2)

(c) Electromagnetic radiation with the frequency calculated in part (b) is incident on the surface of a piece of sodium.

Calculate the maximum possible kinetic energy of an electron that is emitted when a photon of this radiation is incident on the surface.
Give your answer to an appropriate number of significant figures.

maximum kinetic energy = ______________________ J

(3)

(d) Calculate the speed of an electron that has the same de Broglie wavelength as the electromagnetic radiation in part (b).

speed = ______________________ m s^{-1}

(3)

(Total 12 marks)

8 (i) Calculate the longest wavelength of electromagnetic radiation that will cause photoelectric emission at a clean lithium surface.

work function for lithium $\varphi = 4.6 \times 10^{-19}$ J

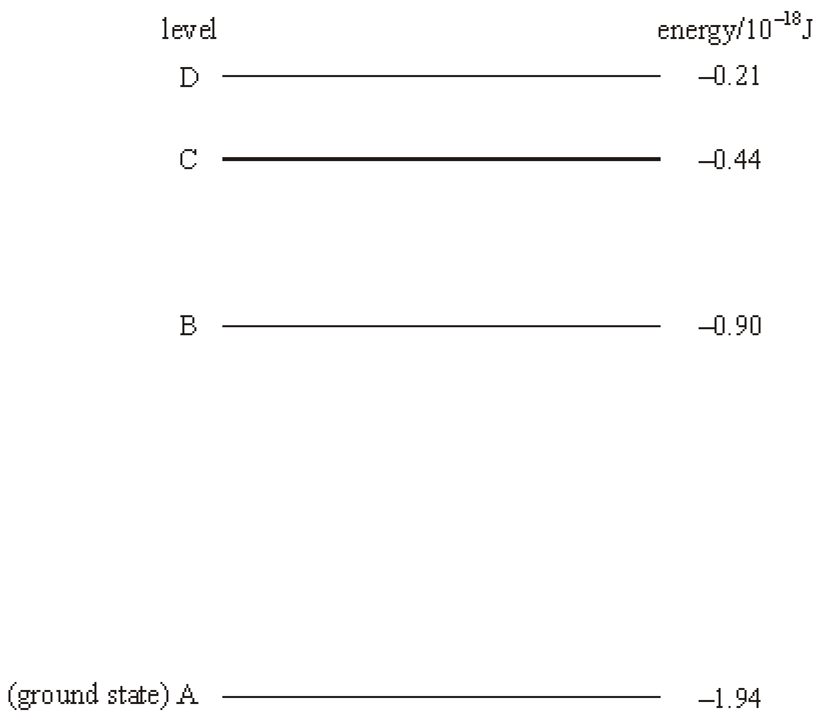
Longest wavelength = ____________________ m

(ii) Calculate maximum kinetic energy of the electrons emitted when electromagnetic radiation of frequency 8.5×10^{14} Hz is incident on the surface.

Maximum energy = ____________________ J

(Total 6 marks)

9 The diagram shows some of the electron energy levels of an atom.



An incident electron of kinetic energy 4.1×10^{-18} J and speed 3.0×10^{6} m s^{-1} collides with the atom represented in the diagram and excites an electron in the atom from level B to level D.

(a) For the incident electron, calculate

(i) the kinetic energy in eV,

____

____

(ii) the de Broglie wavelength.

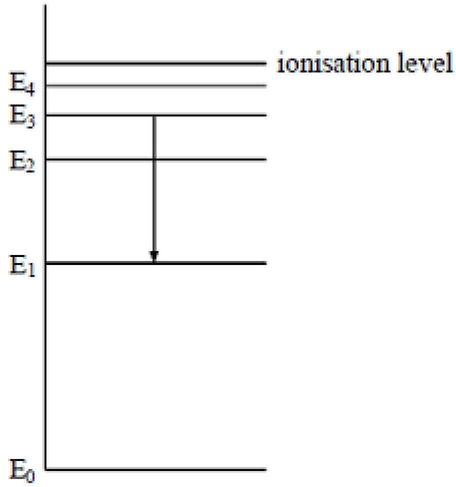
(4)

(b) When the excited electron returns directly from level D to level B it emits a photon. Calculate the wavelength of this photon.

(3)

(Total 7 marks)

10 The diagram shows some energy levels of an atom.



The transition E_3 to E_1 corresponds to the emission of visible light.

A transition corresponding to the emission of infrared radiation could be

A E_1 to E_0

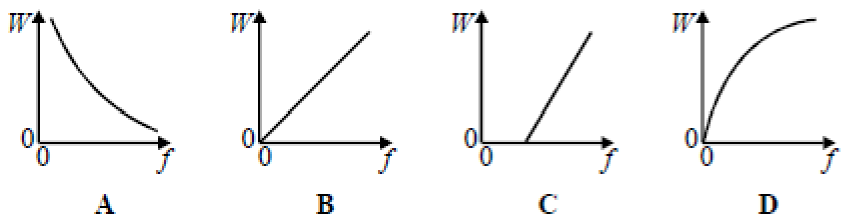
B E_4 to E_1

C E_1 to E_2

D E_3 to E_2

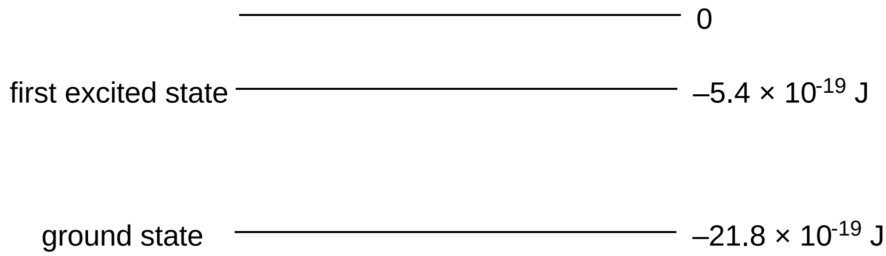
(Total 1 mark)

11 Which one of the graphs best represents the relationship between the energy W of a photon and the frequency f of the radiation?



(Total 1 mark)

12 The diagram shows some of the energy levels for a hydrogen atom.



A free electron of kinetic energy 20.0×10^{-19} J collides with a hydrogen atom in its ground state. The hydrogen atom is excited from its ground state to the first excited state. The kinetic energy of the free electron after the collision is

A 1.8×10^{-19} J

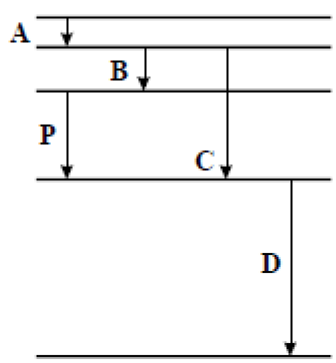
B 3.6×10^{-19} J

C 5.4×10^{-19} J

D 16.4×10^{-19} J

(Total 1 mark)

13 The diagram **drawn to scale** shows some of the energy levels of an atom. Transition **P** results in the emission of a photon of wavelength 4×10^{-7} m.



Which one of the transitions **A**, **B**, **C**, or **D** could result in the emission of a photon of wavelength 8×10^{-7} m?

(Total 1 mark)

Mark schemes

1 (a)

QWC	descriptor	mark range
good-excellent	The candidate provides a comprehensive and logical explanation which recognises that light consists of photons of energy *hf* and that an electron at or near the metal surface can only gain the energy of a single photon when it interacts with a photon. In addition, the candidate should recognise the significance of the work function (of the metal) in this context in relation to the maximum kinetic energy that an emitted electron can have. The candidate should also provide some indication of why the kinetic energy of an emitted electron may be less than the maximum kinetic energy. Although the term 'work function' might not be defined or used, the candidate's explanation should clearly state that each electron needs a minimum amount of energy to escape from the metal.	**5-6**
modest-adequate	The candidate provides a logical and coherent explanation which includes the key ideas including recognition that light consists of photons of energy *hf* and that an electron at or near the metal surface can only gain the energy of a single photon when it interacts with a photon. In addition, the candidate should be aware that each electron needs a minimum amount of energy to escape from the metal. They should appreciate that the kinetic energy of an emitted electron is equal to the difference between the energy it gains from a photon and the energy it needs (or uses) to escape from the metal. However, the explanation may lack a key element such as why the kinetic energy of the emitted electrons varies.	**3-4**
poor-limited	The candidate provides some correct ideas including recognition that light consists of photons of energy *hf* and that electrons in the metal (or at its surface) absorb photons and thereby gain energy. Their ideas lack coherence and they fail to recognise or use in their explanation the key idea that one photon is absorbed by one electron.	**1-2**

The explanations expected in a good answer should include most of the following physics ideas

energy is needed to remove an electron from the surface

work function φ (of the metal) is the minimum energy needed by an electron to escape from the surface

light consists of photons , each of energy $E = hf$

one photon is absorbed by one electron

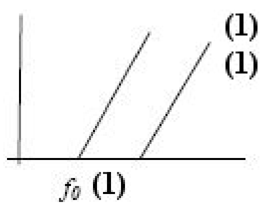
an electron can escape (from the surface) if $hf > \varphi$

kinetic energy of an emitted electron cannot be greater than $hf - \varphi$

an electron below the surface needs to do work/uses energy to reach the surface

kinetic energy of such an electron will be less than $hf - \varphi$

(b) (i)



(ii) parallel line, higher threshold frequency **(1)(1)**

(iii) Planck's constant **(1)**

4

(c) (use of $hf_0 = \phi$)

$hf = 6.63 \times 10^{-34} \times 2 \times 5.6 \times 10^{14}$ **(1)**

$\phi = 3.7(1) \times 10^{-19}$ J **(1)**

$E_k = 2 \times 3.7 \times 10^{-19} - 3.7 \times 10^{-19} = 3.7 \times 10^{-19}$ J **(1)**

3

[13]

2 (a) (i) $f = c/\lambda$ or correct substitution irrespective of powers

C1

5.26×10^{14} (Hz) **not** 5.2×10^{14}

A1

2

(ii) $\Phi = hf$ or substitution irrespective of powers

C1

$3.3 – 3.5 \times 10^{-19}$ J

A1

2

(b) (i) statement or clear use of photoelectric equation

C1

max ke = $1.2 – 1.4 \times 10^{-19}$ (J)

C1

½ mv^2 or substituted values ecf for max ke

C1

$5.1 – 5.6 \times 10^{5}$ ms^{-1} **(cao)**

A1

4

(ii) same intensity and shorter wavelength
=>less photons incident per

B1

second
fewer electrons emitted per second

B1

condone *argument* for unchanged numbers of electrons
(based on 1 to 1 correspondence between photons and
electrons)

2

[10]

3

(a) $v\left(\sqrt{\frac{2E}{m}}\right) = \sqrt{\frac{2 \times 2.0 \times 10^{-18}}{9.1 \times 10^{-31}}}$ **(1)**

$= 2.1 \times 10^{6}$ m s^{-1} **(1)**

2

(b) (i) difference between E_2 and E_0 = 1.94×10^{-18} J **(1)**
which is less than the electron kinetic energy **(1)**

(ii) $(E_2 - E_1) = 3.06 \times 10^{-19}$ **(1)** $(= \frac{hc}{\lambda})$

$\lambda = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{3.06 \times 10^{-19}}$ **(1)** $= 6.5 \times 10^{-7}$ m **(1)**

in visible [or red] region **(1)**

6

(c) for ionisation, p.d. = $\frac{21.8 \times 10^{-19}}{1.6 \times 10^{-19}}$ **(1)** =13.6 V **(1)**

2

[10]

4

(a) (i) no electrons will be released / no current / no effect

B1

work function energy not being exceeded / insufficient photon energy to exceed work function / photon frequency below threshold frequency

B1

(ii) more electrons released per second / current increases

B1

more photons (of sufficient energy) striking metal surface per second

B1

(iii) **answers must be in corresponding pairs below**

cause – B1	**consequence – B1**
electrons collide with air molecules	less electrons reach anode (s^{-1})
photons absorbed by air	less photons reach plate so fewer electrons emitted (s^{-1})
air contaminates plate	(work function ↑) so fewer photons sufficiently energetic to release electrons
cause must be **everything in one pair** of boxes above	ammeter reading or current falls

(b) (i) $\lambda = \frac{h}{mv}$ or correctly substituted values irrespective of powers of 10 **B1**

1.61×10^{-11} m **N.B. "show that"** **B1**

(ii) crystal (or named crystalline material) / graphite **B1**

atomic spacing (condone atomic diameter or distance between nuclei) ≈ λ electrons **B1**

[10]

5 (a) (i) Energy required to remove an electron
Minimum energy required to remove an electron from a (metal) surface **2**

(ii) Read off λ = 550 (nm)
Use of $E = hc / \lambda$ or $E = hf$ and $c = f\lambda$
3.6×10^{-19}
or
Reads st of coordinates correctly
Use of $hc/\lambda = \Phi + E_{k(max)}$
3.6×10^{-19}(J) **3**

(b) $E_k = 9.6 \times 10^{-20}$
J converted to eV / 0.6 eV
4.35 to 4.40×10^{-7} (m), using graph
OR

$E_k = 9.6 \times 10^{-20}$ or $\Phi = 6.4 \times 10^{-19}$(J)

$hc/\lambda = 4.96 \times 10^{-19}$ (using given value in (aii))
or 4.6×10^{-19} using calculated value
or $f = 7.5 \times 10^{14}$(Hz)

4×10^{-7} to 4.4×10^{-7} (m)

Allow ecf for second mark only (i.e. for adding incorrect KE to work function)

3

[8]

6 (a) (Constructive) interference / superposition occurs
or
Waves arrive in phase so produce maximum intensity

Diffraction alone is not enough

B1

1

(b) Correct substitution of numerical value in *h / mv* irrespective of powers of 10

C1

2.1×10^{-11} (m)

A1

2

[3]

7 (a) (i) the <u>minimum energy</u> required by an <u>electron</u>✓
to escape from a (metal)<u>surface</u>✓

if refer to atom / ionisation zero marks

2

(ii) the (minimum) energy to remove an electron(from an atom)✓
from the <u>ground state</u>✓

2

(b) (use of $hf = eV$)
$6.63 \times 10^{-34} \times f = 5.15 \times 1.60 \times 10^{-19}$✓

$f = \dfrac{5.15 \times 1.60 \times 10^{-19}}{6.63 \times 10^{-34}}$✓$= 1.24 \times 10^{15}$(Hz)

if no working and 1.24×10^{15}(Hz) 1 mark

2

(c) (use of $hf = E_k + \Phi$)

$\Phi = 2.28 \times 1.60 \times 10^{-19} = 3.648 \times 10^{-19}$ (J) ✓

$E_k = 5.15 \times 1.60 \times 10^{-19} - 3.648 \times 10^{-19} = 4.59 \times 10^{-19}$ J ✓✓

3 sig figs

if clearly used 1.2×10^{15} then final answer must be to 2 sig. figs. for last mark to be awarded

accept 4.57 in place of 4.59

3

(d) (use of $c = f\lambda$)

$\lambda = \dfrac{3.0\times10^{8}}{1.24\times10^{15}} = 2.42 \times 10^{-7}$ ✓

$v = h / m\lambda = 6.63 \times 10^{-34} / (9.11 \times 10^{-31} \times 2.42 \times 10^{-7}$

$v = 3010$ m s^{-1} ✓✓

first mark minimum working – determination of wavelength

bald answer gets 2 marks

range to 3 sig figs 2900 – 3030

3

[12]

8

(i) recognition that work function = hf_0 or hc/λ_0 **(1)**

rearrangement or correct substitution of values **(1)**

4.3×10^{-7} m **(1)**

(ii) Einstein's equation seen or used **(1)**

work function subtracted from energy of incident photon **(1)**

$1.0(1) \times 10^{-19}$ J **(1)**

[6]

9

(a) (i) k.e. = $\dfrac{4.1\times10^{-18}}{1.6\times10^{-19}}$ **(1)**

= 26 (eV) **(1)** (25.6 eV)

(ii) (use of $\lambda_{dB} = \dfrac{h}{mv}$ gives) $\lambda_{dB} = \dfrac{6.6\times10^{-34}}{9.1\times10^{-31}\times3.0\times10^{6}}$ **(1)**

$= 2.4 \times 10^{-10}$ m **(1)** (2.42×10^{-10} m)

4

(b) (use of $hf = E_1 - E_2$ gives) $f = \dfrac{(0.90 - 0.21) \times 10^{-18}}{6.6 \times 10^{-34}}$ **(1)**

(= 1.05×10^{15} (Hz))

(use of $\lambda = \dfrac{c}{f}$ gives) $\lambda = \dfrac{3.0 \times 10^{8}}{1.05 \times 10^{15}}$ **(1)**

= 2.9×10^{-7} m **(1)** (2.86×10^{-7} m)

3

[7]

10 D

[1]

11 B

[1]

12 B

[1]

13 B

[1]

Examiner reports

1

Part (a) was not answered well and there was much confusion as to the processes involved in the photoelectric effect. However, a significant number of candidates confused the effect with excitation and line spectra. Only a minority of candidates were able to explain why the kinetic energy of the emitted electrons varied. A common response referred to the photons having a variety of energies even though the question stated that the light had a certain frequency. Most answers lacked significant detail such as the idea that a photon interacts with one electron and how threshold frequency and work function are related.

This question assessed quality of written communication and it was clear that most candidates appreciated that their answers needed a logical structure. However, few candidates were able to give a coherent and comprehensive answer.

Part (b) generated better answers although a significant minority of candidates did not appreciate the fact that the gradient of the maximum kinetic energy against frequency graph is the Planck constant.

Part (c) proved more difficult than expected and a number of candidates calculated the energy of the photon using the threshold frequency and failed to calculate the work function.

2

(a) (i) Although the majority of candidates correctly performed a $c = f\lambda$ calculation, this part surprisingly proved to be a stumbling block for a considerable number of candidates. A significant number of candidates incurred a penalty for rounding down their frequency to 5.2×10^{14} Hz (from 5.26×10^{14} Hz).

(ii) Most candidates completing this part did so through the complete photoelectric equation (equating the maximum kinetic energy of the photoelectrons to zero).

(b) (i) Answers to this part either tended to be completely correct or otherwise not score any marks. A high proportion of candidates incorrectly attempted to use the de Broglie relationship, rather than the photoelectric equation.

(ii) This part was not well understood. Many candidates assumed that because the intensity was unchanged, it meant that there were the same number of incident photons per second and so there would be the same number of emitted electrons.

These candidates had failed to appreciate that as the intensity remained constant but the frequency of the photons had increased, there would be fewer photons incident per second and so there would be fewer (but more energetic) electrons released per second.

3

All parts of this question were generally answered well. In part (a) some candidates used an electron mass of 0.00055 u, and some candidates forgot to take the square root.

In part (b) a few candidates calculated the frequency and then did not proceed to evaluate λ. A more common error was to forget to state the region of the electromagnetic spectrum after calculating the wavelength value correctly.

Part (c) was done well.

4 (a) (i) Answers to this were variable with only better candidates making direct references relating the photon energy to the threshold frequency or work function.

(ii) This part was often very poorly answered – very few candidates made reference to increased **rate** of arrival of photons and to the **rate** of emission of photoelectrons. Many candidates appeared to believe that greater intensity meant more energetic photons.

(iii) Again there few totally convincing answers given to this part. Many candidates recognised that the likely outcome would be that the current would fall but only the best candidates were able to give satisfactory reasons for this either in terms of absorption of some photons by the air or the collisions between the photoelectrons and the air molecules (reducing the rate at which photoelectrons reached the anode). Many candidates answered in a manner which indicated confusion between the photons and the photoelectrons.

(b) (i) Most candidates were able to show that the de Broglie wavelength was approximately equal to the given value. Weaker candidates were confused by the difference between c and v in the momentum relationship.

(ii) Most candidates were able to suggest a crystalline or polycrystalline material. The majority of these candidates did not make an overt comparison between the atomic (ionic) spacing and the de Broglie wavelength of the electron.

5 (a) (i) Most appreciated that the work function was the energy to remove an electron. Fewer went on to explain that work function was the <u>minimum</u> energy required and that it refers to electrons <u>at the surface</u>.

(ii) This was generally well done with a high proportion of correct answers. Incorrect read offs from the graph and incorrect powers of 10 were the main causes of failure to complete this part successfully.

(b) Fewer students used the approach of calculating the energy in J, converting to eV and then reading from the graph than the second approach in the marking scheme. Those who used either approach often lost marks due to mixing up energies in J and eV and/or having problems handling powers of 10.

6 (a) Candidates needed to explain the production of the bright ring by constructive interference. The mention of diffraction alone was insufficient.

(b) Most candidates obtained the correct wavelength. Weaker candidates often quoted the equation and then left the mass component blank, suggesting that they did not know that the mass of the electron was on the formula and data sheet. Some substituted the value for the electron charge for the mass.

7 This question on quantum phenomena linked the photoelectric effect with ionisation, two topics which often cause confusion to students. The first parts of the question required students to explain work function and ionization energy. Good explanations were commonly seen but there is still the tendency for students to link work function to electrons escaping from individual atoms.

The remainder of the questions were quantitative and the majority of the calculations involved proved to be accessible. The conversion of electron volts to joules was widely understood and a high proportion of students were able to show that the frequency of radiation required for ionisation was about 1.2×10^{15} Hz. The calculation of the maximum kinetic energy of the electrons emitted had a similar high facility. In this calculation however, students were required to quote their answer to an appropriate number of significant figure. This did present a problem to some as although three significant figures are warranted from the data, if they used 1.2×10^{15} Hz rather than their calculated value, only two should be quoted.

The final calculation of the de Broglie wavelength presented much more of a challenge and only the more able students were able to do this correctly. Weaker students attempted to use the equation for kinetic energy or to use the frequency of the photon instead of calculating the wavelength.

9 Parts (a) and (b) of this question showed errors at different levels of ability. The slightly better candidates used the correct equations but often used the speed of light in the de Broglie relationship. The very weak candidates did not know when to apply $\lambda = \frac{h}{mv}$ or $\lambda = \frac{hc}{E}$. In other cases, the wrong energy was used to calculate the wavelength of a photon and it was not uncommon to see the electron energies at levels D and B being added together.

Part (a) (i) in particular showed a variety of errors. Multiplying, rather than dividing by the electron charge was the obvious error. Some of the better candidates used the electron speed to calculate the kinetic energy, arriving at the energy in joules which had already been given in the question, and then failing to convert this to eV. About 15% of the candidates incurred a significant figure error on this question by quoting an answer to five significant figures.