1 (a) When illuminated with electromagnetic waves, a metal surface can exhibit the photoelectric effect. The maximum wavelength that causes the emission of photoelectrons with zero kinetic energy is 6.8×10^{-7} m.

(i) Show that the threshold frequency for the surface is approximately 4.4×10^{14} Hz.

___

___

___

___

___

(2)

(ii) Show that the work function for the surface is approximately 2.9×10^{-19} J.

___

___

___

___

___

___

(2)

(iii) Calculate the maximum kinetic energy of electrons emitted from the surface when it is illuminated with ultraviolet radiation of frequency 7.8×10^{14} Hz.

___

___

___

___

___

maximum kinetic energy ____________________ J

(2)

(b) Explain why the photoelectric effect cannot be explained by the wave theory of light.

(2)

(Total 8 marks)

2 In the photoelectric effect, electromagnetic radiation incident on a metal surface causes electrons to be emitted from the surface.

(a) State and explain one aspect of the photoelectric effect that suggests the existence of photons.

(2)

(b) Ultra-violet radiation of wavelength 320 nm falls on a sodium surface. Sodium has a *work function* of 3.7×10^{-19} J.

speed of electromagnetic radiation, c $= 3.0 \times 10^{8}$ m s^{-1}

the Planck constant, h $= 6.6 \times 10^{-34}$ J s

mass of an electron, m_e $= 9.1 \times 10^{-31}$ kg

(i) State what is meant by the *work function* of a surface.

(2)

(ii) Show that the maximum kinetic energy of the electrons emitted from the sodium due to the incident ultra-violet radiation is about 2.5×10^{-19} J.

(2)

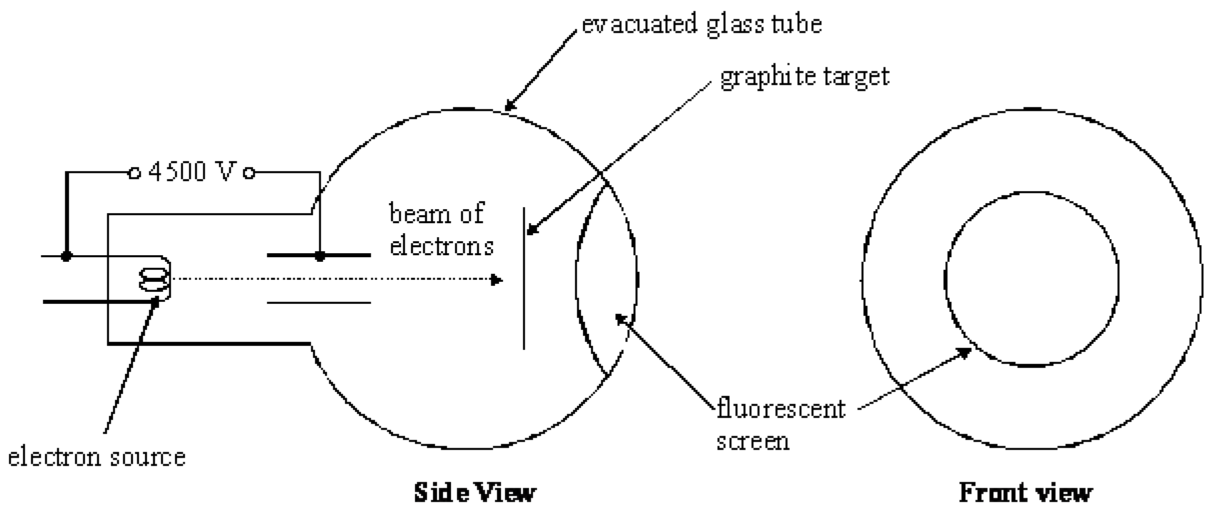
(iii) Determine the de Broglie wavelength associated with the emitted electrons.

(3)

(Total 9 marks)

3 The diagram below shows electrons being fired at a polycrystalline graphite target in a vacuum. The electrons are emitted from a heated cathode and pass through an accelerating p.d. The inside surface on the far side of the chamber is coated with fluorescent material that emits light when the electrons release their energy to it.

Mass of electron $m_e = 9.1 \times 10^{-31}$ kg
Planck constant $h = 6.6 \times 10^{-34}$ J s



(a) The electrons travel at a speed of 4.0×10^{7} m s^{-1}. Calculate their de Broglie wavelength.

(1)

(b) Sketch on the **front view** of the fluorescent screen shown in the diagram the pattern of light you would expect to see emitted by the fluorescent material.

Explain why this pattern suggests that electrons have wave-like properties.

____

____

____

____

(2)

(c) Explain **one** aspect of the experiment that suggests that electrons have particle-like properties.

____

____

____

____

(2)

(Total 5 marks)

4 (a) In the photoelectric effect equation

$$hf = \phi + E_k$$

state what is meant by

hf ____

____

ϕ ____

____

E_k ____

____

(3)

(b) Monochromatic light of wavelength 3.80×10^{-7} m falls with an intensity of 6.0 μW m^{-2} on to a metallic surface whose work function is 3.2×10^{-19} J.
Using data from the *Data Sheet*, calculate

(i) the energy of a single photon of light of this wavelength,

(ii) the number of photons emitted per second from 1.0×10^{-6} m^2 of the surface if a photon has a 1 in 1000 chance of ejecting an electron,

(iii) the maximum kinetic energy which one of these photoelectrons could possess.

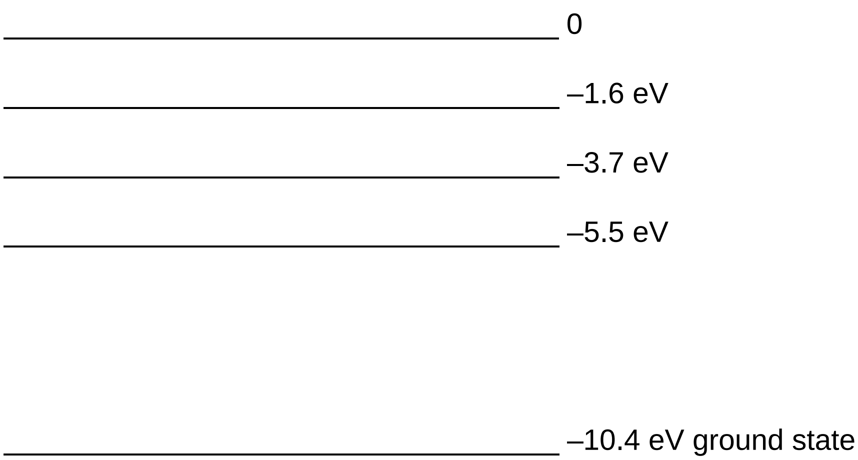
(5)

(Total 8 marks)

5 (a) Describe how the concept of *energy levels* is useful in the explanation of *line spectra*.

(3)

(b) The diagram represents some energy levels of the mercury atom.



charge of electron = 1.6×10^{-19} C
the Planck constant = 6.6×10^{-34} J s
speed of light in vacuo = 3.0×10^{8} m s^{-1}

(i) What is the ionisation energy, in J, of the mercury atom?

(ii) Determine which transition corresponds to the emission of radiation of wavelength 141 nm.

(iii) State the region of the spectrum in which you would expect to find radiation of this wavelength.

(7)
(Total 10 marks)

6 Electrons may be emitted when electromagnetic radiation is incident on a metallic surface

(a) The photoelectric equation is

$$hf = \phi + E_k,$$

where h is the Planck constant and f is the frequency of the incident radiation.

Explain the meanings of

work function, ϕ ______________________________

____

E_k ______________________________

____

(2)

(b) In a typical experiment to investigate the photoelectric effect, E_k was measured for photons of different wavelengths, λ ,and the values in the table were obtained.

λ/nm	200	300	400	500	600
$E_k \times 10^{-19}$/J	6.72	3.30	1.68	0.66	0.05
$\frac{1}{\lambda}$ / nm^{-1}					

(i) By rearranging the photoelectric equation, show that a graph of E_k (y-axis) plotted against $\frac{1}{\lambda}$ (x-axis) will give a straight line.

____

____

____

(ii) Use the above data to plot this graph on the grid provided and use your graph to determine values for ϕ, in eV, and the Planck constant, h.

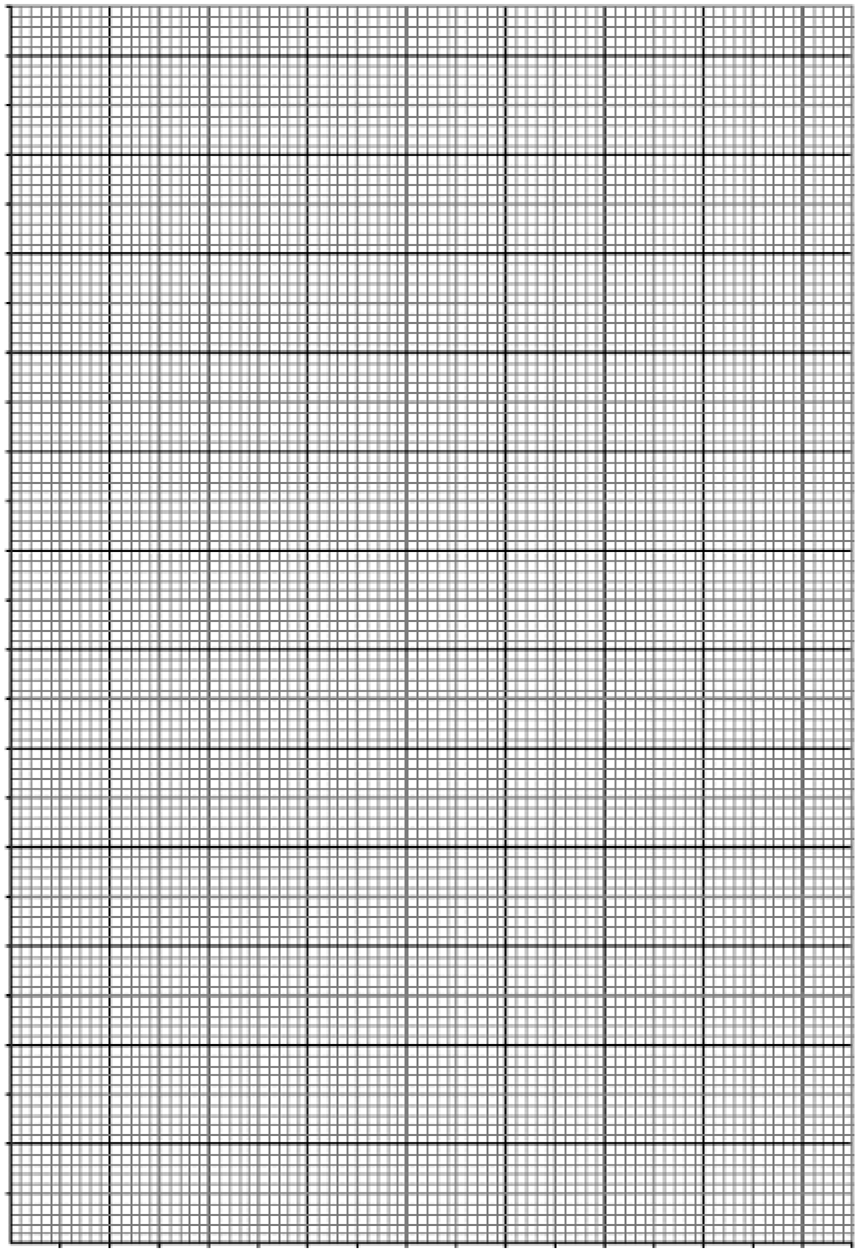
____

____

____

____

____



(9)

(c) Using the same axes, sketch the graph which you would expect to obtain if the experiment were repeated with a metal having a larger value of ϕ.

(2)

(d) In a simple demonstration of the photoelectric effect, a metal plate is given a negative charge and illuminated with, in turn,

(i) red light from a laser,

(ii) an ultraviolet lamp.

The ultraviolet lamp causes the plate to lose charge but the laser has no effect. Explain why this is so.

___

___

___

(2)
(Total 15 marks)

7 (a) Electrons and electromagnetic waves exhibit properties of both waves and particles. Suggest evidence which indicates that

(i) electrons have wave properties,

___

(ii) electromagnetic radiation has particle properties,

___

(iii) electromagnetic radiation has wave properties.

___

(3)

(b) Calculate the de Broglie wavelength of an electron travelling at 5.0×10^6 m s^{-1}. You should ignore relativistic effects.

___

___

___

___

(3)
(Total 6 marks)

8 The photoelectric effect is one piece of evidence that suggests that light behaves like a stream of particles or photons.

(a) State what is meant by the threshold frequency in an experiment to investigate the photoelectric effect.

___

___

___

(2)

(b) State and explain the effect of increasing the intensity of light on the rate at which electrons are emitted.

____

____

____

____

(2)

(c) In an experiment to investigate the photoelectric effect the radiation incident on the surface caused the emission of electrons of energy 1.5×10^{-19} J. The work function of the surface was known to be 3.2×10^{-19} J.

The Planck constant h is 6.6×10^{-34} J s.
The speed of electromagnetic radiation is 3.0×10^{8} m s^{-1}.
The mass of an electron is 9.1×10^{-31} kg.

(i) Calculate the wavelength of the incident radiation.

(2)

(ii) Calculate the de Broglie wavelength of the emitted electrons.

(3)
(Total 9 marks)

9 (a) Calculate the wavelength of a γ-ray photon which has an energy of 1.6×10^{-15} J.

____

____

(2)

(b) An X-ray photon is generated which has the same energy as the γ-ray photon described in part (a).

(i) How do the speeds in a vacuum of these two photons compare?

____

(ii) How do their abilities to penetrate a given material compare?

____

(2)
(Total 4 marks)

10 (a) (i) State what is meant by the *wave-particle duality* of electromagnetic radiation.

____

____

(ii) Which aspect of the dual nature of electromagnetic radiation is demonstrated by the photoelectric effect?

____

____

____

(2)

(b) A metal plate is illuminated with ultra violet radiation of frequency 1.67×10^{15} Hz. The maximum kinetic energy of the liberated electrons is 3.0×10^{-19} J.

(i) Calculate the work function of the metal.

____

____

____

____

____

(ii) The radiation is maintained at the same frequency but the intensity is doubled. State what changes, if any, occur to the number of electrons released per second and to the maximum kinetic energy of these electrons.

number per second ____

maximum kinetic energy ____

(iii) The metal plate is replaced by another metal plate of different material. When illuminated by radiation of the same frequency no electrons are liberated. Explain why this happens and what can be deduced about the work function of the new metal.

____

____

____

____

____

(8)

(Total 10 marks)

11 In a photoelectric experiment, light is incident on the metal surface of a photocell. Increasing the intensity of the illumination at the surface leads to an increase in the

A work function

B minimum frequency at which electrons are emitted

C current through the photocell

D speed of the electrons

(Total 1 mark)

12 An electron has a kinetic energy E and a de Broglie wavelength λ. The kinetic energy is increased to $4E$. What is the new de Broglie wavelength?

A $\frac{\lambda}{4}$

B $\frac{\lambda}{2}$

C λ

D 4λ

(Total 1 mark)

13 Monochromatic radiation from a source of light (source A) is shone on to a metallic surface and electrons are emitted from the surface. When a second source (source B) is used no electrons are emitted from the metallic surface. Which property of the radiation from source A must be greater than that from source B?

A amplitude

B frequency

C intensity

D wavelength

(Total 1 mark)

14 When comparing X-rays with UV radiation, which statement is correct?

A X-rays have a lower frequency.

B X-rays travel faster in a vacuum.

C X-rays do not show diffraction and interference effects.

D Using the same element, photoelectrons emitted using X-rays have the greater maximum kinetic energy.

(Total 1 mark)

15 The intensity of a monochromatic light source is increased. Which of the following is correct?

	Energy of an emitted photon	**Number of photons emitted per second**	
A	increases	increases	
B	increases	unchanged	
C	unchanged	increases	
D	unchanged	unchanged	

(Total 1 mark)

Mark schemes

1 (a) (i) $f = c/\lambda$ seen in this form

C1

4.41×10^{14} seen

A1

2

(ii) $\Phi = hf$

C1

2.917×10^{-19} to 2.93×10^{-19} seen

A1

2

(iii) $h(7.8 \times 10^{14})$ – their (ii)

C1

2.2×10^{-19} (J) to 2.3×10^{-19} (J)

A1

2

(b) no photoemission below threshold frequency (even with bright light)

B1

wave theory would allow gradual accumulation of energy to cause emission

B1

2

[8]

2 (a) relevant observation explains why this supports photons or does not support waves

Examples

electrons are emitted with no noticeable delay

if wave theory time would elapse while an electron gains sufficient energy to leave the surface or wtte

there is a threshold frequency below which there are no electrons emitted

photons have to have sufficient energy to cause emission and photon energy is frequency related

B1

or if a wave energy could build up over time to cause electron emission

for a given frequency of light there is a given max KE for the emitted electron

a photon gives all its energy to an electron to remove it and give it KE

intensity of the light does not affect the KE of the emitted electrons

high intensity waves would be expected to give higher kinetic energy to an electron

do **not** allow increased intensity increases number of electron

B1

(b) (i) energy to remove an electron or to cause photoelectric emission

C1

minimum energy to remove an electron (from the surface)

A1

(2)

(ii) photon energy = hc / λ

or E_k(max) = hc / λ – ϕ

B1

max KE = = 6.2×10^{-19} J – 3.7×10^{-19} stated explicitly

allow 2 for correct substitution in Ek(max) = hc / λ – ϕ

B1

(2)

(iii) λ = h / mv

C1

velocity of electron = 7.4×10^{5} m s^{-1}

or momentum of electron = 6.75×10^{-250} (kg m s^{-1})

C1

wavelength = 9.78 or 9.8×10^{-10} m (value correct)

A1

(3)

[9]

3 (a) $1.8/1.81 \times 10^{-11}$ m

B1

1

(b) circular bands of light on diagram

B1

diffraction/interference effect **or** electron λ ≈ atomic spacing in graphite

B1

2

(c) state correct and appropriate particulate aspect

B1

quote evidence *from this expt* that shows electrons possess aspect

B1

2

e.g.
electrons carry momentum/kinetic energy to screen
excite other electrons in atoms/cause emission of energy/light
or
electrons carry charge
can be accelerated by electric field/p.d.
etc

[5]

4 (a) hf = **photon** energy **(1)**
ϕ = work function **(1)**
E_k = **maximum** kinetic energy of photoelectrons **(1)**

(3)

(b) (i) $E\left(=\frac{hc}{\lambda}\right)=\frac{6.6\times10^{-34}\times3\times10^{8}}{3.8\times10^{-7}}=5.23\times10^{-19}$ J **(1)**

(ii) energy on surface = 6.0×10^{-12} J mm^{-2} s^{-1} **(1)**

$N=\frac{6.0\times10^{-12}}{5.23\times10^{-16}}=1.1(5)\times10^{4}$ s^{-1} **(1)(1)**

(iii) $E_k\left(=\frac{hc}{\lambda}-\phi\right)=(5.2(3)–3.2)$ **(1)** $\times10^{-19}=2.0\times10^{-19}$ J **(1)**

(5)

[8]

5 (a) only certain energies [or energy changes] allowed **(1)**
a line [or photon] corresponds to transition between levels **(1)**
each transition [or energy change]
corresponds to a definite wavelength [or frequency] **(1)**

3

(b) (i) $E_{ion}=10.4\times1.6\times10^{-19}$ (or10.4 eV) **(1)**
$=1.66\times10^{-18}$ (J) **(1)**

(ii) $E\left(=\frac{hc}{\lambda}\right)=\frac{6.6\times10^{-34}\times3.0\times10^{8}}{141\times10^{-9}}$ **(1)**

$=1.40\times10^{-18}$ J **(1)**
= 8.8 eV **(1)**
which is from 1.6 to 10.4 **(1)**

(iii) ultra-violet **(1)**

7

[10]

6 (a) ϕ is <u>minimum</u> energy needed to remove electron **(1)**
E_k is <u>maximum</u> energy of emitted electron **(1)**

(2)

(b) (i) $E_k=hf-\phi$

$f=\frac{c}{\lambda}\ \therefore E_k=hc\left(\frac{1}{\lambda}\right)-\phi$ **(1)**

cf $y=mx+c$ **(1)**

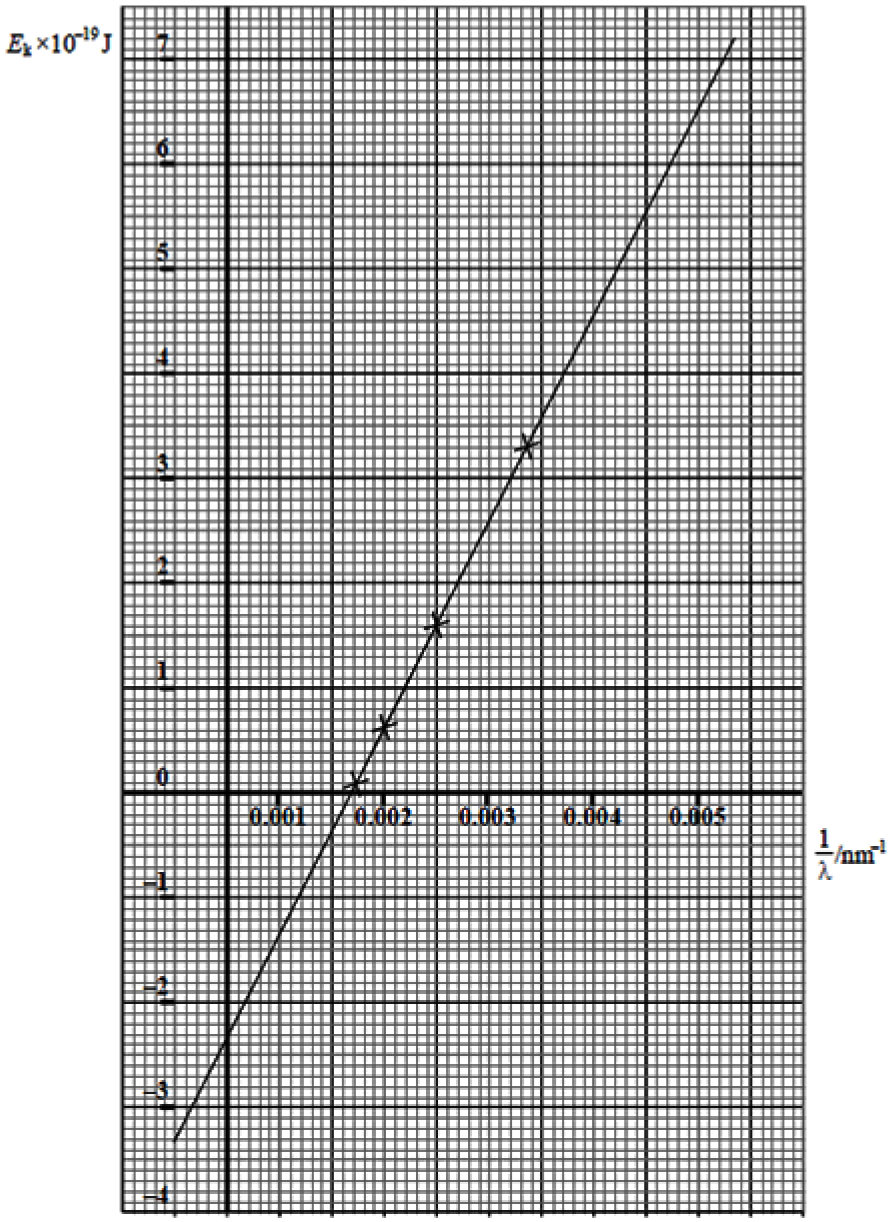
(ii)

λ / nm	200	300	400	500	600
$E_k \times 10^{-19}$ J	6.72	3.30	1.68	0.66	0.05
$\frac{1}{\lambda}$ / nm^{-1}	0.0050	0.0033	0.0025	0.0020	0.0017

$\frac{1}{\lambda}$ values correct **(1)**

both axes correctly labelled **(1)**
five points correctly plotted **(1)**
sensible scale and straight line **(1)**

graph for this question



from intercept, $\phi = 3.3 \times 10^{-19}$ J **(1)** = 2.1 eV **(1)**

use of large triangle gives gradient $\left(= \frac{6.7 \times 10^{-19}}{(5.00 - 1.65) \times 10^{6}} \right) = 2.01 \times 10^{-25}$

$h = \frac{\text{gradient}}{c}$ $= 6.7 \times 10^{-34}$ J s **(1)**

(max 9)

(c) straight line to right of present curve **(1)**
parallel to it **(1)**

(2)

(d) ultraviolet high frequency **(1)**
above f_0 for emission **(1)**
[or red light low frequency **(1)**
below f_0 for emission **(1)**]

[*alternative (d)*
ultraviolet [red light] photon energy is high [low] **(1)**
above [below] work function **(1)**]

(2)

[15]

7

(a) (i) (wave property) (electron) diffraction **(1)**

(ii) (particle-property) photoelectric effect **(1)**

(iii) (wave property) interference / diffraction / refraction **(1)**

(3)

(b) (momentum of electron =) $mv = 9.11 \times 10^{-31} \times 5.0 \times 10^{6}$ **(1)**

$(= 4.56 \times 10^{-24}$ (kg m s^{-1})) **(1)**

[($\lambda = h/mv$ gives) $\lambda = 6.6(3) \times 10^{-34} / 4.56 \times 10^{-24}$ **(1)**

(allow e.c.f. for value of mv)

$= 1.5 \times 10^{-10}$ m **(1)** (1.45×10^{-10} m)

(3)

[6]

8

(a) the frequency needed to liberate an electron (electrons) from the surface of a material
or
minimum frequency to cause photoelectric effect

C1

the minimum frequency of the radiation / light / photon needed to liberate an electron (electrons) from (the surface of) a material or from the surface

A1

(2)

(b) the rate increases or more electrons per second

M1

there are more photons striking the surface each second

A1

no change in rate if frequency is below threshold frequency – allow 1

(2)

(c) (i) Calculation using *hc / E* for (4.7 or 1.5 or 3.2) $\times 10^{-19}$ J
use of 1.5 leads to 1.32×10^{-6};
use of 3.2 leads to 6.2×10^{-7}

C1

4.2×10^{-7} m

A1

(2)

(ii) use of 1.5 × 10^{-19} J

B1

$p = \sqrt{(2mE)}$ and $\lambda = h / p$ or $E = ½ mv^2$ and $\lambda = h / mv$

C1

correct answer for their energy
1.26 × 10^{-9} m for 1.5 × 10^{-19} J
1.2 × 10^{-9} m for 1.7 × 10^{-19} J
0.86 × 10^{-9} m for 3.2 × 10^{-19} J
0.71 × 10^{-9} m for 4.7 × 10^{-19} J

A1

(3)

[9]

9

(a) $\lambda \left(= \frac{hc}{E} \right) = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{1.6 \times 10^{-15}}$ **(1)** $= 1.2(4) \times 10^{-10}$ m **(1)**= 1.2(4) × 10^{-10} m **(1)**

(2)

(b) (i) same **(1)**

(ii) same **(1)**

(2)

[4]

10

(a) (i) electromagnetic radiation behaves either as a particle or as a wave **(1)**

(ii) (electromagnetic radiation) behaves as a particle **(1)**

(2)

(b) (i) $hf = \varphi + E_k$ **(1)**
φ = (6.63 × 10^{-34} × 1.67 × 10^{15}) – (3.0 × 10^{-19}) **(1)**
= 8.1 × 10^{-19} **(1)** J **(1)** (8.07 × 10^{-19})

(ii) (number per second) doubled **(1)**
(maximum kinetic energy) remains constant **(1)**

(iii) (all) electrons have insufficient energy to leave the (new) metal **(1)**
the work function of the (new) metal is greater than hf
[or the work function of the (new) metal is greater than
that of the original metal] **(1)**

The Quality of Written Communication marks were awarded primarily for the quality of answers to this part.

(8)

[10]

11

C

[1]

12

B

[1]

13

B

[1]

14 D

[1]

15 C

[1]

Examiner reports

1

Many candidates found the calculations in part (a) to be accessible. However, candidates should be aware that simply getting the correct answer in not sufficient when they have been asked to 'show that'. In these cases they must be clear with their selection of equations, manipulation, substitution and in dealing with powers of ten. They should also quote their answer to a greater degree of provision than number mentioned in the question in order to demonstrate that they have performed the calculation completely. There were a surprising number of candidates that did not attempt this part of the question.

Answers to part (b) were poor. It seems that candidates were familiar with the effect but they were not able to articulate the logic of why it demonstrates that light, in this case, is not acting as a wave.

3

(a) This simple calculation of the de Broglie wavelength was well done by many.

(b) A pleasing number could give an indication of the likely diffraction pattern on the front of the tube and then go on to offer an explanation of the wave behaviour in terms of diffraction or interference effects.

(c) This was less impressive. Only about one-third of candidates reasoned that (for example) charge is a particulate property and that it is demonstrated by the acceleration of the electron in the electric field.

5

In part (a) marks were often lost because of carelessly worded answers. It is difficult to believe that some candidates have seen line spectra as they seem convinced that spectra is singular. The most common score was probably one mark. Only a small proportion of candidates referred to the electron having certain allowed energy levels. Most candidates knew that a photon, or less often a line, was emitted when an electron dropped from one energy level to another, but few unambiguously related the difference in energy of the levels to the frequency or wavelength of the emitted line. There was some confusion with absorption spectra.

Part (b) proved to be much easier and many candidates scored 6 or 7 marks. A few candidates thought that the ionisation energy was 1.6eV, or forgot to change to J. Most candidates obtained 8.8 eV in part (b)(ii), but some candidates dropped a mark by not recognising the wavelength as being in the ultraviolet. The commonest wrong answer was ϒ rays.

6

Many candidates found part (a) to be straightforward and did it well. Those candidates who failed usually omitted the words 'minimum' and 'maximum'. A few candidates thought that E_k was the maximum energy of a *photon*.

In general, part (b)(i) was answered well, but several candidates failed because they omitted the speed of light from the relationship between frequency and wavelength. Most candidates calculated the $1 / \lambda$ values correctly in part (b)(ii), but some (including those who used dot notation to indicate recurring figures) lost a mark for incorrect use of significant figures. Other incorrect notations included $3\frac{1}{3} \times 10^{-3}$ and $1\frac{2}{3} \times 10^{-3}$. Graphs were usually plotted reasonably with axes correctly labelled, points correctly plotted and a straight line drawn. Many candidates knew how to calculate φ and h, but few could deal with powers of ten correctly, particularly when given nm^{-1} as a starting point. Notable omissions in part (b)(ii) were the units of h and the 10^{-19} factor when reading the intercept for φ.

7 There was some evidence that quite a number of candidates were not prepared for this topic. Candidates who were conversant with it usually gave a completely correct answer, but others usually failed to score at all. In the calculation in part (b), a number of candidates started with $\frac{1}{2}mv^2$, showing that they were unfamiliar with the subject.

8 (a) A large number of candidates gave a complete answer. However, failure to state that it is the frequency of the electromagnetic radiation (or light) that is relevant or to state that electrons were emitted from the surface were causes of many lost marks. A significant proportion of the candidates did not know what happens in the photoelectric effect and had the idea that photons were emitted due to the incidence of electrons.

(b) Many gave loose answers that did not refer to the *rate* at which electrons were emitted and stated simply ‘more electrons emitted’. The fact that higher intensity meant more photons arriving per second per square metre was not well known.

(c) Many were confused between the equations that they needed to use for electromagnetic radiation and for particles. Correct answers to the two parts were, therefore, frequently seen the wrong way round.

(i) Those who used the correct formula in this part often used the wrong energy (usually 1.5×10^{19} J).

(ii) Although many quoted h / mv they were clearly confused and 20 to 30% of the candidates used c as the velocity. Most who knew the correct process used 1.5×10^{19} J in their attempt to determine the velocity but errors with arithmetic were common.

10 Overall, the candidates had a sound understanding of the photoelectric effect and there was a good response to part (a). The most common error was for candidates to refer to the wave-particle duality of electrons rather than of electromagnetic radiation.

The calculation in part (b)(i) was carried out correctly by most candidates but a large number of answers were presented without units. Good candidates had no difficulty with part (ii) but many simply stated that “the number of electrons released per second increases”, rather than “the number doubles”. Answers to part (iii) indicated that candidates seemed to have a much better understanding of the photoelectric effect than those who sat the examination in January. Pleasingly few candidates referred to electrons in shells, ionisation or the electronic bond with a single atom. The weaker candidates often lost marks because they expressed ideas in an unclear fashion, for example, “the work function needs to be higher in the new metal” was a statement commonly seen.