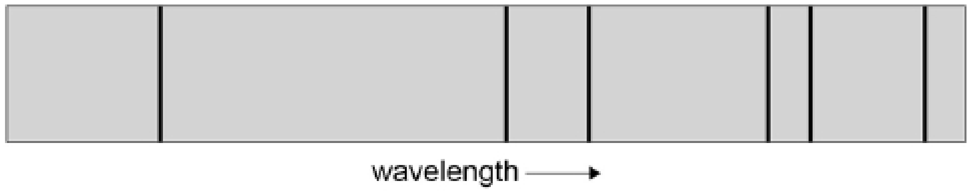
1 The diagram below shows the line spectrum of a gas.



Explain how line spectra are produced. In your answer you should describe:

- how the collisions of charged particles with gas atoms can cause the atoms to emit photons.
- how spectral lines are explained by the concept of discrete energy levels.

(Total 6 marks)

2 (a) What phenomenon can be used to demonstrate the wave properties of electrons?

____

(1)

(b) Calculate the wavelength of electrons travelling at a speed of 2.5×10^5 ms^{-1}.

Give your answer to an appropriate number of significant figures.

wavelength ____________________ m

(3)

(c) Calculate the speed of muons with the same wavelength as these electrons.

mass of muon = 207 × mass of electron

speed ____________________ ms^{-1}

(2)

(Total 6 marks)

3 (a) State what is meant by the wave-particle duality of electrons.

____

____

____

(1)

(b) Electrons of wavelength 1.2×10^{-10} m are required to investigate the spacing between planes of atoms in a crystal.

(i) Calculate the momentum of an electron of this wavelength stating an appropriate unit.

momentum of electron = ______________________

(3)

(ii) Calculate the speed of such an electron.

speed of electron = ______________________ $m\ s^{-1}$

(2)

(iii) Calculate the kinetic energy of such an electron.

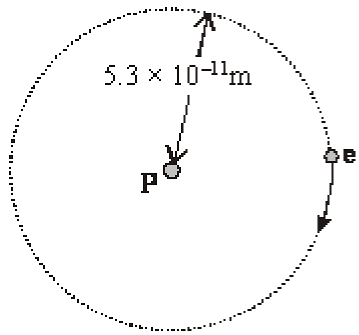
kinetic energy of electron = ______________________ J

(2)

(Total 8 marks)

4 The Bohr model of a hydrogen atom assumes that an electron **e** is in a circular orbit around a proton **P**. The model is shown schematically in **Figure 1**.

Figure 1



In the ground state the orbit has a radius of 5.3×10^{-11} m. At this separation the electron is attracted to the proton by a force of 8.1×10^{-8} N.

(a) State what is meant by the ground state.

____

____

(1)

(b) (i) Show that the speed of the electron in this orbit is about 2.2×10^{6} m s^{-1}.

mass of an electron = 9.1×10^{-31} k g

(ii) Calculate the de Broglie wavelength of an electron travelling at this speed.

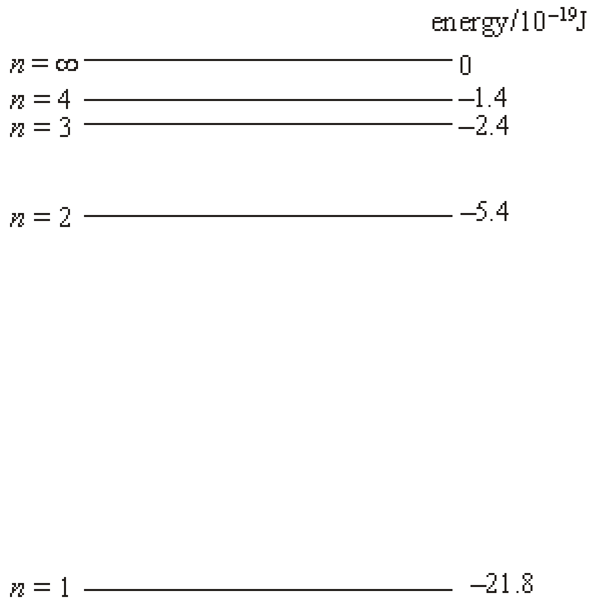
Planck constant = 6.6×10^{-34} J s

(iii) How many waves of this wavelength fit the circumference of the electron orbit? Show your reasoning.

(7)

(c) The quantum theory suggests that the electron in a hydrogen atom can only exist in certain well-defined energy states. Some of these are shown in **Figure 2**.

Figure 2



An electron **E** of energy 2.5×10^{-18} J collides with a hydrogen atom that is in its ground state and excites the electron in the hydrogen atom to the n = 3 level.

Calculate

(i) the energy that is needed to excite an electron in the hydrogen atom from the ground state to the n = 3 level,

(ii) the kinetic energy of the incident electron **E** after the collision,

(iii) the wavelength of the lowest energy photon that could be emitted as the excited electron returns to the ground state.

speed of electromagnetic radiation = 3.0×10^{8} m s^{-1}

(5)

(Total 13 marks)

5 (a) The mercury atoms in a fluorescent tube are excited and then emit photons in the ultraviolet region of the electromagnetic spectrum.

(i) Explain how the mercury atoms become excited.

____

____

____

____

____

____

(3)

(ii) Explain how the excited mercury atoms emit photons.

____

____

____

____

____

____

(2)

(b) Explain how the ultraviolet photons in the tube are converted into photons in the visible part of the electromagnetic spectrum.

____

____

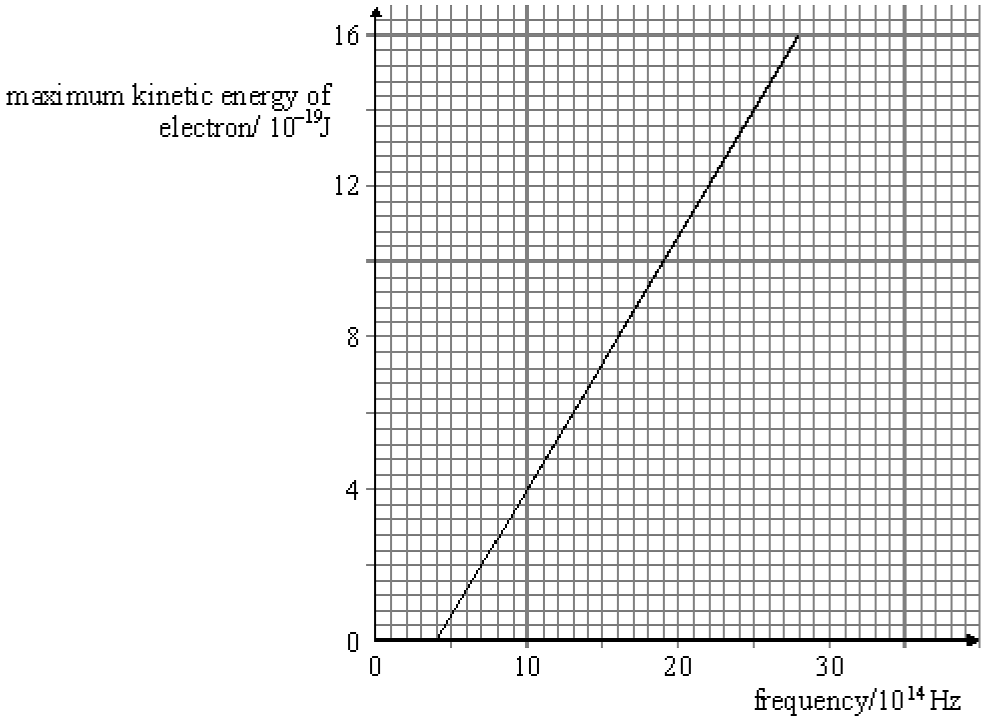
____

____

(2)

(Total 7 marks)

6 The diagram below shows how the maximum kinetic energy of electrons emitted from the cathode of a photoelectric cell varies with the frequency of the incident radiation.



(a) Calculate the maximum wavelength of electromagnetic radiation that can release photoelectrons from the cathode surface.

Speed of electromagnetic radiation in a vacuum = 3.0×10^{8} m s^{-1}

(3)

(b) Another photoelectric cell uses a different metal for the photocathode. This metal requires twice the minimum energy for electron release compared to the metal in the first cell.

(i) Draw a line on the diagram to show the graph you would expect to obtain for this second cell.

(1)

(ii) Explain your answer with reference to the Einstein photoelectric equation.

____

____

____

(2)

(Total 6 marks)

7 (a) Describe what occurs in the photoelectric effect.

____

____

____

____

(2)

(b) Violet light of wavelength 380 nm is incident on a potassium surface.

Deduce whether light of this wavelength can cause the photoelectric effect when incident on the potassium surface.

work function of potassium = 2.3 eV

(4)

(c) The photoelectric effect provides evidence for light possessing particle properties.

State and explain **one** piece of evidence that suggests that light also possesses wave properties.

___

___

___

___

___

(2)

(Total 8 marks)

8 The photoelectric effect can be demonstrated by illuminating a negatively charged plate, made from certain metals, with ultraviolet (UV) light and showing that the plate loses its charge.

(a) Explain why, when ultraviolet light is shone on a **positively** charged plate, no charge is lost by the plate.

____

____

____

____

____

____

____

(2)

(b) Threshold frequency and work function are important ideas in the study of the photoelectric effect.

Tables 1 and **2** summarise the work functions of three metals and photon energies of three UV light sources.

Table 1

Metal	**Work function / eV**
Zinc	4.3
Iron	4.5
Copper	4.7

Table 2

Light source	**Photon energy / eV**
1	4.0
2	4.4
3	5.0

Discuss the combinations of metal and UV light source that could best be used to demonstrate the idea of threshold frequency and the idea of work function.

____

____

____

____

____

____

(6)

(c) Calculate the maximum kinetic energy, in J, of the electrons emitted from a zinc plate when illuminated with ultraviolet light.

work function of zinc = 4.3 eV

frequency of ultraviolet light = 1.2×10^{15} Hz

maximum kinetic energy ____________________ J

(3)

(d) Explain why your answer is a maximum.

____

____

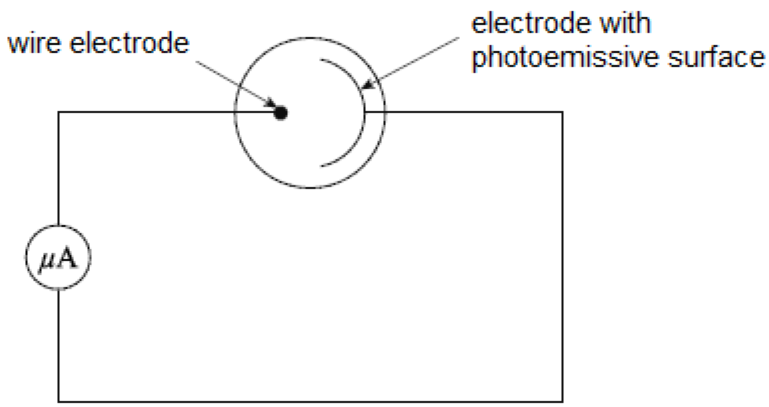
____

(1)

(Total 12 marks)

9 **Figure 1** shows a photocell which uses the photoelectric effect to provide a current in an external circuit.

Figure 1



(a) Electromagnetic radiation is incident on the photoemissive surface.

Explain why there is a current only if the frequency of the electromagnetic radiation is above a certain value.

___

___

___

___

___

___

(3)

(b) State and explain the effect on the current when the intensity of the electromagnetic radiation is increased.

___

___

___

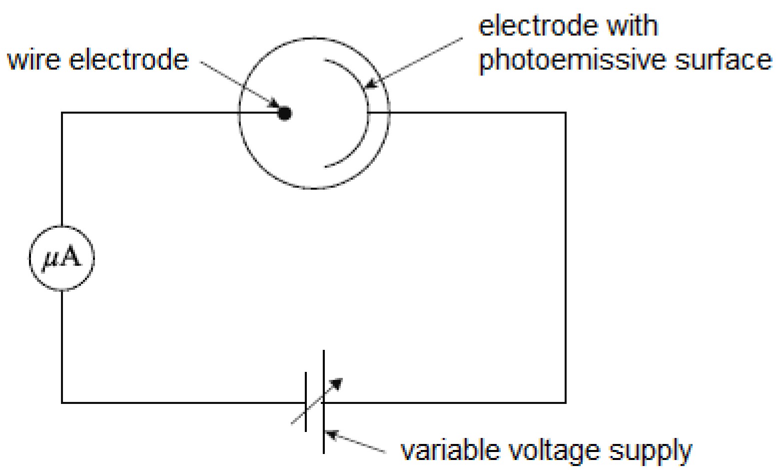
___

(2)

(c) A student investigates the properties of the photocell. The student uses a source of electromagnetic radiation of fixed frequency and observes that there is a current in the external circuit.

The student then connects a variable voltage supply so the positive terminal is connected to the electrode with a photoemissive surface and the negative terminal is connected to the wire electrode. As the student increases the supply voltage, the current decreases and eventually becomes zero. The minimum voltage at which this happens is called the stopping potential. The student's new circuit is shown in **Figure 2**.

Figure 2



The photoemissive surface has a work function of 2.1 eV. The frequency of the electromagnetic radiation the student uses is 7.23×10^{14} Hz.

Calculate the maximum kinetic energy, in J, of the electrons emitted from the photoemissive surface.

maximum kinetic energy = ____________________ J

(3)

(d) Use your answer from **part (c)** to calculate the stopping potential for the photoemissive surface.

stopping potential = ____________________ V

(1)

(e) The student increases the frequency of the electromagnetic radiation.

Explain the effect this has on the stopping potential.

___

___

___

___

___

___

(3)

(Total 12 marks)

10 In an experiment to demonstrate the photoelectric effect, a charged metal plate is illuminated with light from different sources. The plate loses its charge when an ultraviolet light source is used but not when a red light source is used.

What is the reason for this?

A The intensity of the red light is too low. ☐

B The wavelength of the red light is too short. ☐

C The frequency of the red light is too high. ☐

D The energy of red light photons is too small. ☐

(Total 1 mark)

11 Which of the following classes of electromagnetic waves will **not** ionise neutral atoms?

What is the reason for this?

A ultraviolet

B X radiation

C gamma radiation

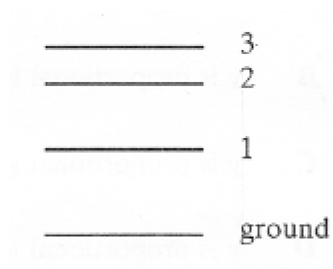
D microwave

(Total 1 mark)

12 The values of the lowest three energy levels in a particular atom are shown in the table.

The diagram shows these levels together with the ground state of the atom.

Level	Energy/eV
3	−0.85
2	−1.51
1	−3.39



When an electron moves from level 3 to level 1, radiation of frequency 6.2×10^{14} Hz is emitted.

What is the frequency of the radiation emitted when an electron moves from level 2 to level 1?

A 2.3×10^{14} Hz

B 3.5×10^{14} Hz

C 4.6×10^{14} Hz

D 8.3×10^{14} Hz

(Total 1 mark)

13 Experiments on which of the following suggested the wave nature of electrons?

A	electron diffraction by a crystalline material	⬭
B	β^- decay	⬭
C	line spectra of atoms	⬭
D	the photoelectric effect	⬭

(Total 1 mark)

14 Electrons and protons in two beams are travelling at the same speed. The beams are diffracted by objects of the same size.

Which correctly compares the de Broglie wavelength λ_e of the electrons with the de Broglie wavelength λ_p of the protons and the width of the diffraction patterns that are produced by these beams?

	comparison of de Broglie wavelength	diffraction pattern	
A	$\lambda_e > \lambda_p$	electron beam width > proton beam width	⬭
B	$\lambda_e < \lambda_p$	electron beam width > proton beam width	⬭
C	$\lambda_e > \lambda_p$	electron beam width < proton beam width	⬭
D	$\lambda_e < \lambda_p$	electron beam width < proton beam width	⬭

(Total 1 mark)

Mark schemes

1 **The mark scheme gives some guidance as to what statements are expected to be seen in a 1 or 2 mark (L1), 3 or 4 mark (L2) and 5 or 6 mark (L3) answer. Guidance provided in section 3.10 of the '*Mark Scheme Instructions*' document should be used to assist in marking this question.**

Level	Criteria	QoWC
L3 5−6 marks	Good discussion of both elements in question with at least 4 points mentioned in each element	The student presents relevant information coherently, employing structure, style and sp&g to render meaning clear. The text is legible.
L2 3−4 marks	Good discussion with at least 3 points in one element and 2 points in the other element	The student presents relevant information and in a way which assists the communication of meaning. The text is legible. Sp&g are sufficiently accurate not to obscure meaning.
L1 1−2 marks	Discussion of one element only incorporating at least two points.	The student presents some relevant information in a simple form. The text is usually legible. Sp&g allow meaning to be derived although errors are sometimes obstructive.
0	Unsupported combination or no relevant analysis	The student's presentation, spelling, punctuation and grammar seriously obstruct understanding.

Collisions

- *Energy from collision of charged particles transfers to electrons in gas molecules.*
- *Electrons excited to higher energy levels.*
- *The more energy the electrons absorb the higher the energy levels reached.*
- *Electrons are unstable at higher energy levels so will fall back down.*
- *When it falls down it will emit a photon.*

Formation of spectral lines

- *Photon energy = hf/ or photon energy proportional to frequency.*
- *Spectral lines are at specific wavelengths.*
- *Each spectral line corresponds to an electron falling down to a lower energy state.*
- *Energy gap,* $\Delta E = hc/\lambda$
- *Larger energy gap means higher energy photon is emitted so shorter wavelength or vice versa.*

Responses with no mention of photons are likely to receive zero marks.

6

[6]

2 (a) (electron) diffraction / interference / superposition ✓

Accept derfraction

1

(b) (*use of* $\lambda = h / mv$)

$\lambda = 6.63 \times 10^{-34} / (9.11 \times 10^{-31} \times 2.5 \times 10^{5})$ ✓

$\lambda = 2.9 \times 10^{-9}$m ✓ ✓ (2 sig figs.)

3

(c) $v = 2.5 \times 10^{5} / 207$ ✓

$v = 1200$ m s^{-1} ✓

OR use $v = h / m\lambda$ with CE from part (b)

Answer alone gets 2 marks

2

[6]

3 (a) electrons can have wavelike properties and particle like properties **(1)**

1

(b) (i) (use of $\lambda = h/mv$)

$mv = 6.63 \times 10^{-34}/1.2 \times 10^{-10}$ **(1)**

$mv = 5.5 \times 10^{-24}$ **(1)** kg m s^{-1} **(1)** (or Ns)

(ii) $v = 5.5 \times 10^{-24}/9.11 \times 10^{-31}$ **(1)**

$v = 6.1 \times 10^{6}$ m s^{-1} **(1)**

(iii) (use of $E = ½mv^2$)

$E = ½ \times 9.11 \times 10^{-31} \times (6.1 \times 10^{6})^2$ **(1)** (must see working or equation)

$E = 1.6(9) \times 10^{-17}$ J **(1)** (no working max 1)

7

[8]

4 (a) lowest energy state/level that the electron can occupy

or state in which electron needs most energy to be released

B1

1

or the level of an unexcited electron (not lowest orbit)

(b) (i) force = mv^2/r or $mr\omega^2$ and $v = r\omega$

B1

$8.1 \times 10^{-8} = 9.1 \times 10^{-31} \times v^2/5.3 \times 10^{-11}$
or (v^2 =) 4.72×10^{12} seen

B1

2.17 × 106 (m s^{-1})

B1

(ii) $\lambda = h/mv$ or $6.6 \times 10^{-34}/9.1 \times 10^{-31} \times 2.2 \times 10^6$

C1

7

3.3×10^{-10} m

A1

(iii) circumference = $2\pi 5.3 \times 10^{-11} = 3.3 \times 10^{-10}$ m

M1

1 (allow e.c.f. from (ii))

A1

(c) (i) $1.9(4) \times 10^{-18}$ J

B1

(ii) 5.6×10^{-19} J (e.c.f. 2.5×10^{-18} − their (i))

B1

(iii) energy difference $E = 3 \times 10^{-19}$ J
(condone any difference)

C1

E = hc/λ *or* E = hf *and* c=fλ

or their E = $6.6 \times 10^{-34} \times 3.0 \times 108/\lambda$

C1

6.6 or 6.7×10^{-7} m

A1

5

[13]

5 (a) (i) electrons passing through tube collide with electrons in mercury atom ✓

Allow mercury atoms collide with each other

transferring energy / atom gains energy from a collision ✓
causing orbital electrons / electrons in mercury atom to move to higher energy level ✓

Atomic electrons move from ground state

3

(ii) (each) excited electron / atom relaxes to a lower (energy) level ✓

allow excited electron / atom de-excites / relaxes

Allow excited electron / atom relaxes to ground state

Condone moves for relaxes

emitting a photon of energy <u>equal</u> to the energy difference between the levels ✓

2

(b) coating absorb (uv) photons (causing excitation) / (uv)photons collide with electrons in the coating (causing excitation) / electrons in coating are excited

allow <u>atoms</u> in coating absorb (uv) photons (causing excitation)

Atomic <u>electrons</u> de-excite indirectly to previous lower level (and in doing so emit lower energy photons) ✓

Owtte (must convey smaller difference between energy levels in a transition) cascade

2

[7]

6 (a) Use of 4×10^{14}

C1

Use of $c = f\lambda$

C1

7.5×10^{-7} m

A1

3

(b) line parallel to first intersecting *x*-axis at twice threshold freq

B1

(i) gradient is *h* so unchanged

B1

(ii) intersection with *x*-axis is double because
hf = φ at zero ke for e^-

B1

3

[6]

7 (a) Photons of light incident on the metal surface cause the emission of electrons ✓

The electrons emitted are those near the surface of the metal✓

2

(b) Use of = hc / λ condone errors in powers of 10✓

5.2×10^{-19} J✓

Converts their energy in J to eV or work function to J

photon energy = 3.3 eV or work function = 3.7×10^{-19} J✓

Compares the two values and draws conclusion✓

4

(c) Diffraction effects (spreading of light) when light passes through a single slit

OR

interference patterns (light and dark fringes) using two slits or diffraction grating✓

Only waves diffract and interfere✓

2

[8]

8 (a) The process involves the ejection of electrons which are negatively charged. ✓

1

Any electrons ejected will only make the positive charge greater. ✓

1

(b) **The mark scheme gives some guidance as to what statements are expected to be seen in a 1 or 2 mark (L1), 3 or 4 mark (L2) and 5 or 6 mark (L3) answer. Guidance provided in section 3.10 of the '*Mark Scheme Instructions*' document should be used to assist in marking this question.**

Mark	Criteria	QoWC
6	Both ideas fully analysed, with full discussion of alternatives.	The student presents relevant information coherently, employing structure, style and sp&g to render meaning clear. The text is legible.
5	Both ideas analysed with supporting discussion but without alternatives	
4	Both ideas analysed, with one dealt with satisfactorily and the other with some supporting discussion	The student presents relevant information and in a way which assists the communication of meaning. The text is legible. Sp&g are sufficiently accurate not to obscure meaning.
3	Both ideas analysed, with only one dealt with satisfactorily	
2	One idea analysed with some supporting discussion	The student presents some relevant information in a simple form. The text is usually legible. Sp&g allow meaning to be derived although errors are sometimes obstructive.
1	One idea analysed, with little supporting discussion	
0	Unsupported combination or no relevant analysis	The student's presentation, spelling, punctuation and grammar seriously obstruct understanding.

The following statements are likely to be present.
To demonstrate threshold frequency:
The metal should be kept the same, and the light source varied.
Using any metal, and light sources 1 and 3,
no charge will be lost with light source 1
but charge will be lost with light source 3
because light source three has a greater photon energy
and therefore frequency (from E=hf)
and is above the threshold frequency
as the photon energy is greater than the work function of the metal

but light source 1 has a photon energy less than the work function of the metal
so its frequency is below the threshold frequency.
To demonstrate work function
The light source should be kept the same, and the metal varied
Use light source 2 as the other two will either cause all three metals to lose their charge, or none of the metals to lose their charge.
Use each metal in turn, so that zinc loses its charge, due to its low work function, but copper and iron do not lose their charge.

6

(c) Work function in joules = $1.6 \times 10^{-19} \times 4.3 = 6.9 \times 10^{-19}$ J ✓

The first mark is for converting the work function into J

1

Use of hf = work function + KE_{max}

The second mark is for substituting into the photoelectric equation

1

$KE_{max} = hf$ – work function
$= (6.63 \times 10^{-34}) \times (1.2 \times 10^{15}) + 6.9 \times 10^{-19}$ ✓
$= 7.9 \times 10^{-19} - 6.9 \times 10^{-19}$
$= 1.0 \times 10^{-19}$ J ✓

The third mark is for the final answer

Allow 1.1

1

(d) The work function is the minimum amount of energy needed to remove the electron from the zinc surface ✓

Alternative

Reference to max ke corresponding to emission of surface electrons whilst electrons from deeper in the metal will be emitted with smaller ke

1

[12]

9 (a) energy of <u>photon</u> ✓

1

is greater than the work function ✓

1

so electrons are emitted ✓

1

if correct reference to threshold frequency and no mention of work function then only score one of first two marks and can be awarded third mark

(b) increased intensity means more photons incident per second ✓

only need to see per second once

1

current greater OR more electrons emitted per second ✓

rate of photons incident OK (or rate of electrons emitted)

1

(c) *(use of $hf = \varnothing + E_k$)*

$\varnothing = 2.1 \times 1.6 \times 10^{-19} = 3.36 \times 10^{-19}$ ✓(J)

if incorrect or no conversion to J then CE for next two marks

1

$E_k = 6.63 \times 10^{-34} \times 7.23 \times 10^{14} - 3.36 \times 10^{-19}$

1

$E_k = 1.4(3) \times 10^{-19}$ ✓(J)

1

(d) *(use of $eV = E_k$)*

$V_S = 1.43 \times 10^{-19} / 1.6 \times 10^{-19} = 0.89$ (V) ✓

CE from 05.3

RANGE 0.70 – 0.90

1

(e) stopping potential would be greater ✓

1

because the <u>energy</u> of the <u>photons</u> (of the electromagnetic radiation) would be greater ✓

1

(hence) <u>maximum</u> kinetic energy of (photo)electrons would be greater ✓

1

[12]

10 D

[1]

11 D

[1]

12 C

[1]

13 A

[1]

14 A

[1]