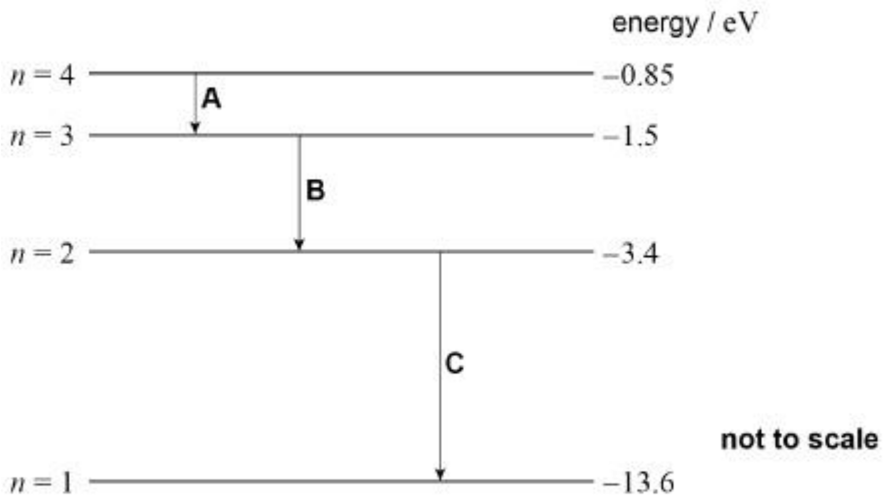
# EM radiation and quantum phenomena

**Q1.**

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




An excited hydrogen atom can emit photons of certain discrete frequencies. Three possible transitions are shown in the diagram.

(a) The transitions shown in the diagram result in photons being emitted in the ultraviolet, visible and infrared regions of the electromagnetic spectrum.

To which region of the spectrum do the emitted photons belong?

Tick (✓) the correct box for each transition, **A**, **B** and **C**.

| Transition | Ultraviolet | Visible | Infrared |
|---|---|---|---|
| **A** | ☐ | ☐ | ☐ |
| **B** | ☐ | ☐ | ☐ |
| **C** | ☐ | ☐ | ☐ |

**(1)**

(b) Two ways to excite a hydrogen atom are by collision with a free electron or by the absorption of a photon.

Explain why, for a particular transition, the photon must have an exact amount of energy whereas the free electron only needs a minimum amount of kinetic energy.

___________________________________________________________________

(3)

(c) The surface of a sample of caesium is exposed to photons emitted in each of the three transitions shown in the diagram.

The threshold frequency of caesium is $5.1 \times 10^{14}$ Hz

Determine whether any of these transitions would produce photons that would cause electrons to be emitted from the surface of caesium.

(3)

(d) Photons each with energy 12.1 eV are incident on the surface of the caesium sample.

Calculate the maximum speed of electrons emitted from the caesium.

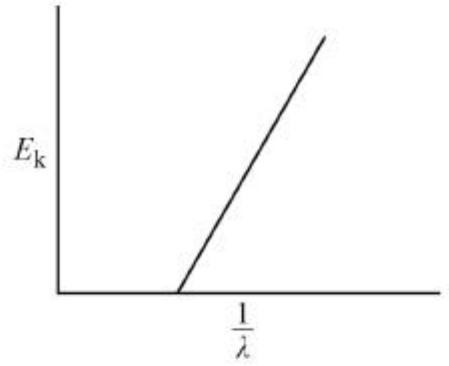
maximum speed = ____________________ m s$^{-1}$

(3)

**(Total 10 marks)**

## Q2.

The graph shows how the maximum kinetic energy $E_k$ of photoelectrons emitted from a metal surface varies with the reciprocal of the wavelength $\lambda$ of the incident radiation.




What is the gradient of this graph?

**A** $c$ ☐

**B** $h$ ☐

**C** $hc$ ☐

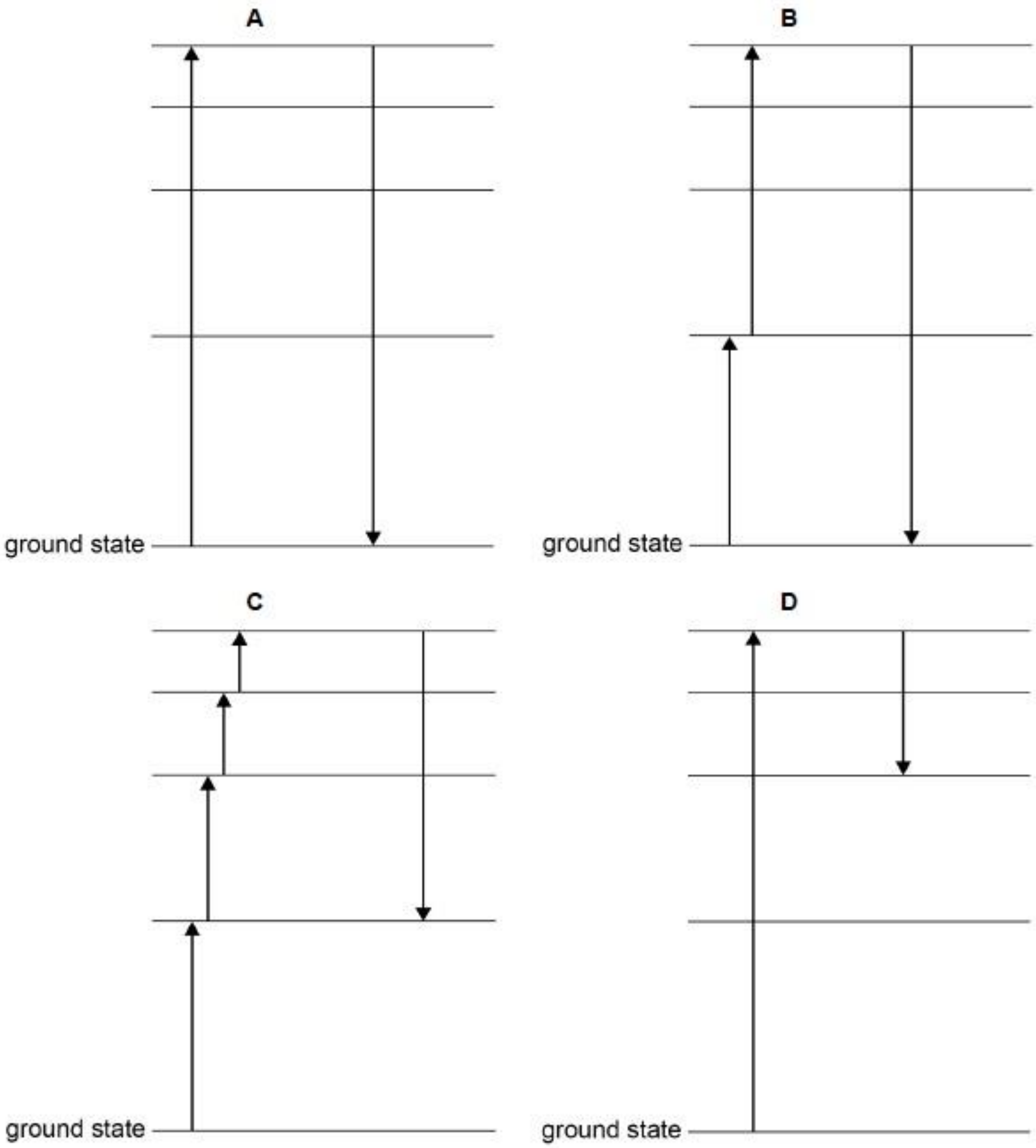
**D** $\frac{h}{c}$ ☐

**(Total 1 mark)**

## Q3.

An atom in the inner coating of a fluorescent tube absorbs a photon of ultraviolet radiation. This causes excitation of the atom from its ground state. A photon of visible light is then emitted.

Which energy level diagram represents this process?




**A** ⬭

**B** ⬭

**C** ⬭

**D** ⬭

**(Total 1 mark)**

## Q4.

A particle of mass $m$ has a kinetic energy of $E$.

What is the de Broglie wavelength of this particle?

A $\frac{h}{\sqrt{(2Em^2)}}$ ○

B $\frac{h}{\sqrt{2E}}$ ○

C $\frac{h}{\sqrt{\left(\frac{2E}{m^2}\right)}}$ ○

D $\frac{h}{\sqrt{2Em}}$ ○

**(Total 1 mark)**

## Q5.

Which row links both the photoelectric effect and electron diffraction to the properties of waves and particles?

| | Photoelectric effect | Electron diffraction | |
|---|---|---|---|
| **A** | Particle property | Particle property | ○ |
| **B** | Wave property | Wave property | ○ |
| **C** | Particle property | Wave property | ○ |
| **D** | Wave property | Particle property | ○ |

**(Total 1 mark)**

## Q6.

The table shows results of an experiment to investigate how the de Broglie wavelength $\lambda$ of an electron varies with its velocity $v$.

| $v$ / $10^7$ m s$^{-1}$ | $\lambda$ / $10^{-11}$ m |
|---|---|
| 1.5 | 4.9 |
| 2.5 | 2.9 |
| 3.5 | 2.1 |

(a) Show that the data in the table are consistent with the relationship $\lambda \propto \frac{1}{v}$

**(2)**

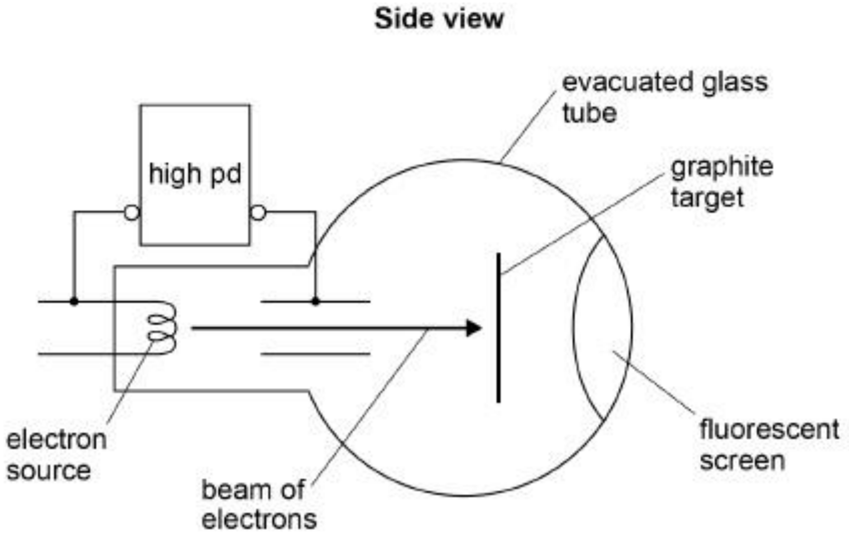
(b) Calculate a value for the Planck constant suggested by the data in the table.

Planck constant = ____________________ J s

**(2)**

(c) **Figure 1** shows the side view of an electron diffraction tube used to demonstrate the wave properties of an electron.

**Figure 1**

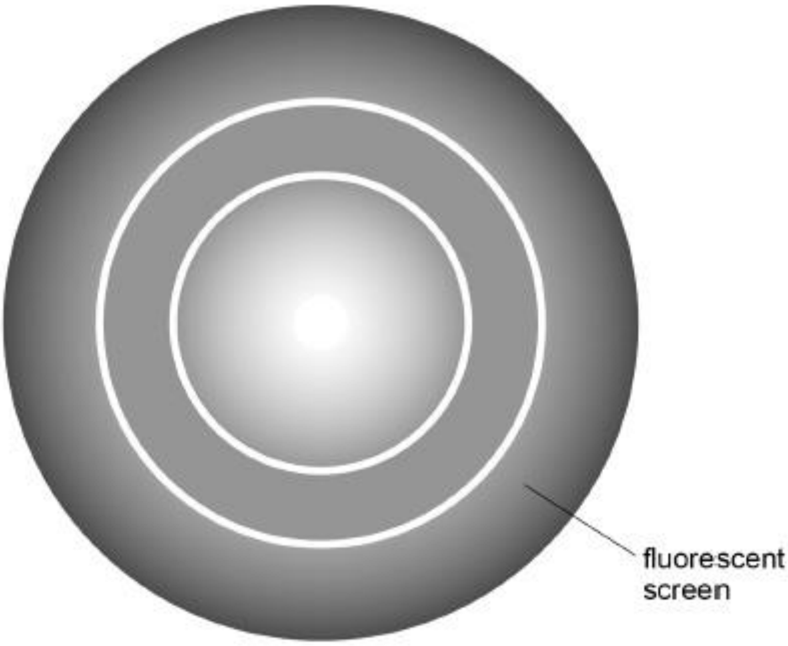



An electron beam is incident on a thin graphite target that behaves like the slits in a diffraction grating experiment. After passing through the graphite target the electrons strike a fluorescent screen.

**Figure 2** shows the appearance of the fluorescent screen when the electrons are incident on it.

**Figure 2**

Front view




Explain how the pattern produced on the screen supports the idea that the electron beam is behaving as a wave rather than as a stream of particles.

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**(3)**

(d) Explain how the emission of light from the fluorescent screen shows that the electrons incident on it are behaving as particles.

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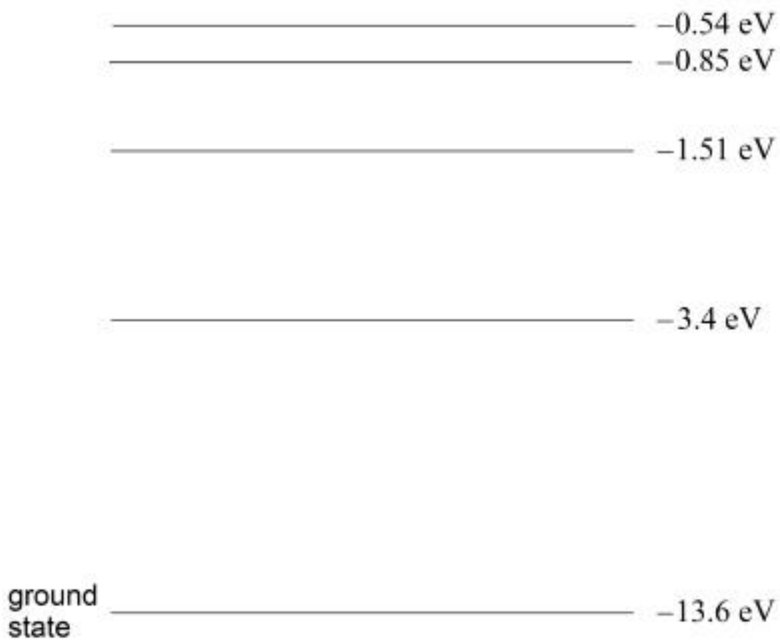
(3)

**(Total 10 marks)**

## Q7.

The diagram shows an energy-level diagram for a hydrogen atom.




Electrons, each having a kinetic energy of $2.0 \times 10^{-18}$ J, collide with atoms of hydrogen in their ground state. Photons are emitted when the atoms de-excite.

How many different wavelengths can be observed with incident electrons of this energy?

**A** 1

**B** 3

**C** 6

**D** 7

**(Total 1 mark)**

## Q8.

Photons of wavelength 290 nm are incident on a metal plate. The work function of the metal is 4.1 eV

What is the maximum kinetic energy of the emitted electrons?

**A** 0.19 eV ○

**B** 4.3 eV ○

**C** 6.9 eV ○

**D** 8.4 eV ○

**(Total 1 mark)**

## Q9.

Which statement suggests that electrons have wave properties?
Tick (✓) the correct answer.

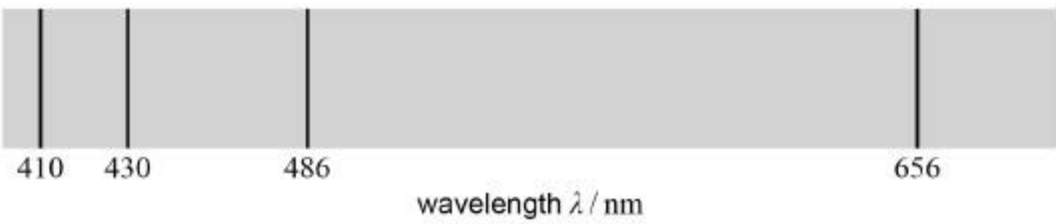
| | |
|---|---|
| Electrons are emitted in photoelectric effect experiments. | ☐ |
| Electrons are released when atoms are ionised. | ☐ |
| Electrons produce dark rings in diffraction experiments. | ☐ |
| Electron transitions in atoms produce line spectra. | ☐ |

**(Total 1 mark)**

## Q10.

In a discharge tube a high potential difference is applied across hydrogen gas contained in the tube. This causes the hydrogen gas to emit light that can be used to produce the visible line spectrum shown in **Figure 1**.

**Figure 1**

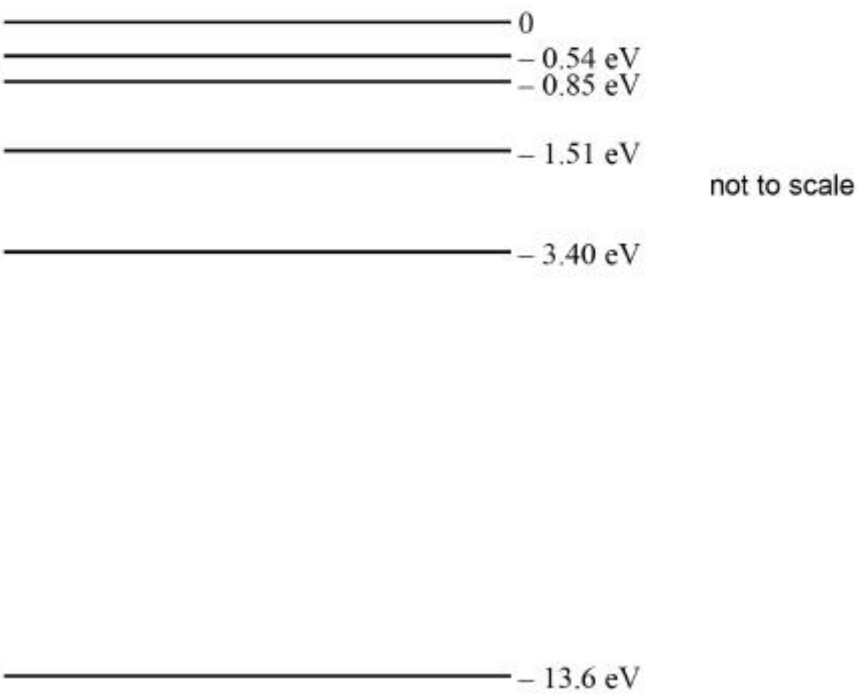



The visible line spectrum in **Figure 1** has been used to predict some of the electron energy levels in a hydrogen atom.

The energy levels predicted from the visible line spectrum are those between 0 and −3.40 eV in the energy level diagram.

Some of the predicted energy levels are shown in **Figure 2**.

**Figure 2**




(a) Calculate the energy, in eV, of a photon of light that has the lowest frequency in the visible hydrogen spectrum shown in **Figure 1**.

energy of photon = ______________________________ eV

**(3)**

(b) Identify the state of an electron in the energy level labelled 0.

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**(1)**

(c) Identify the state of an electron that is in the energy level labelled –13.6 eV.

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**(1)**

(d) Explain why the energy levels are negative.

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**(1)**

(e) Discuss how the discharge tube is made to emit electromagnetic radiation of specific frequencies.

In your answer you should:

- explain why there must be a high potential difference across the tube
- discuss how the energy level diagram in **Figure 2** predicts the spectrum shown in **Figure 1**
- show how one of the wavelengths of light is related to two of the energy levels in the energy level diagram.

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**(6)**

**(Total 12 marks)**

## Q11.

When light of a certain frequency greater than the threshold frequency of a metal is directed at the metal, photoelectrons are emitted from the surface.
The power of the light incident on the metal surface is doubled.

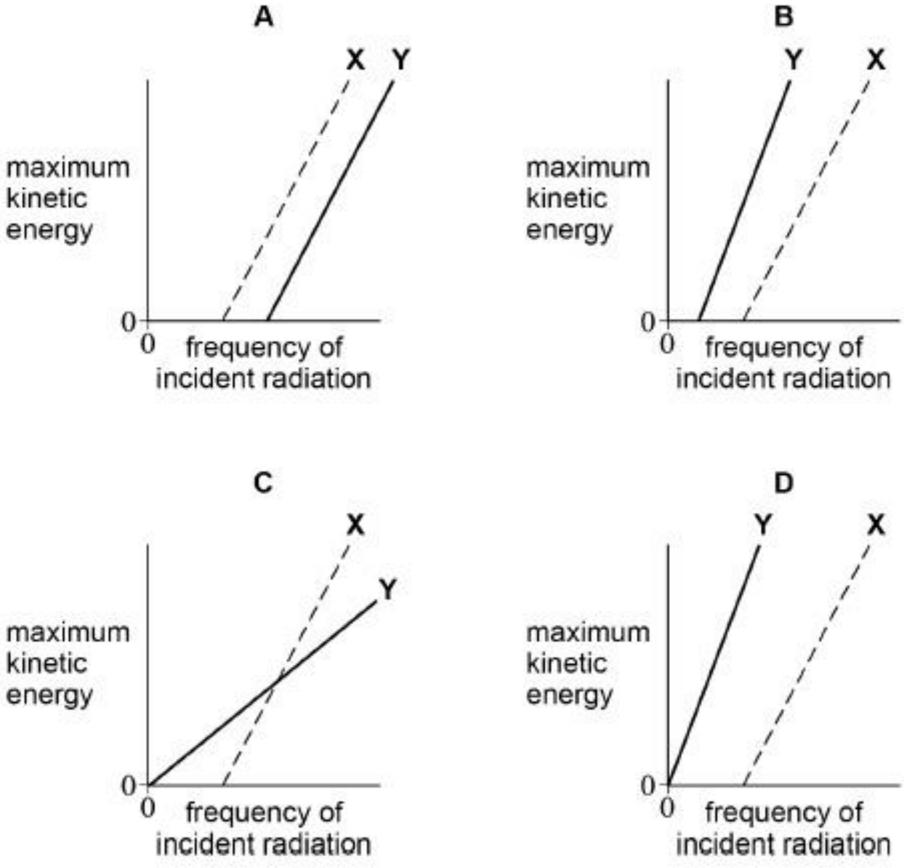
Which row shows the effect on the maximum kinetic energy and the number of photoelectrons emitted per second?

| | **Maximum kinetic energy** | **Number of photoelectrons emitted per second** | |
|---|---|---|---|
| **A** | remains unchanged | remains unchanged | ☐ |
| **B** | doubles | remains unchanged | ☐ |
| **C** | remains unchanged | doubles | ☐ |
| **D** | doubles | doubles | ☐ |

## Q12.

Line **X** on the graphs below shows how the maximum kinetic energy of emitted photoelectrons varies with the frequency of incident radiation for a particular metal.

Which graph shows the results for a metal **Y** that has a higher work function than **X**?




**A** ☐

**B** ☐

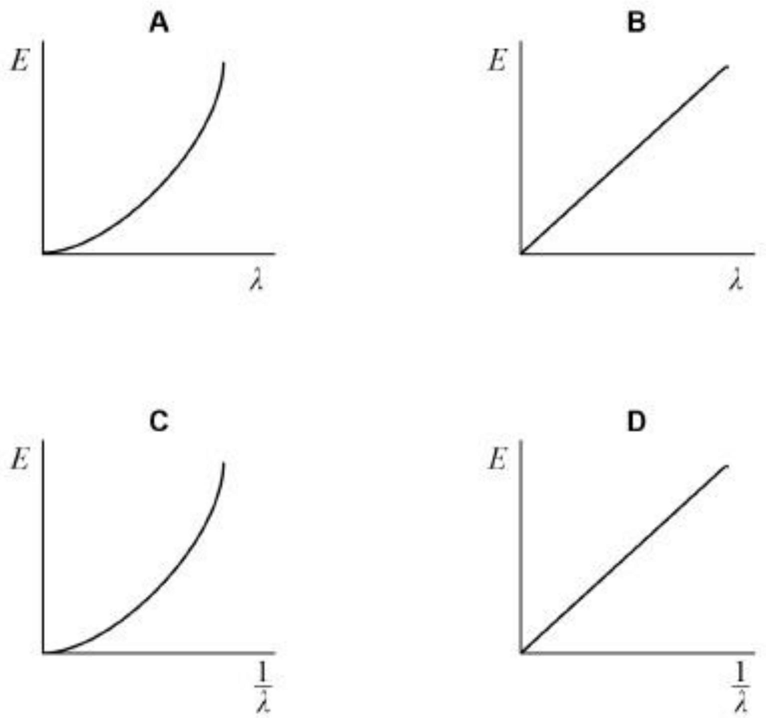
**C** ☐

**D** ☐

**(Total 1 mark)**

## Q13.

Which graph best shows the relationship between photon energy $E$ and wavelength $\lambda$ of a photon of electromagnetic radiation?




**A** ⬭

**B** ⬭

**C** ⬭

**D** ⬭

**(Total 1 mark)**

## Q14.

A beam of light of wavelength $\lambda$ is incident on a clean metal surface and photoelectrons are emitted. The wavelength of the light is halved but energy incident per second is kept the same.

Which row in the table is correct?

| | Maximum kinetic energy of the emitted photoelectrons | Number of photoelectrons emitted per second | |
|---|---|---|---|
| **A** | Increases | Unchanged | ⬭ |
| **B** | Decreases | Increases | ⬭ |
| **C** | Increases | Decreases | ⬭ |
| **D** | Decreases | Unchanged | ⬭ |

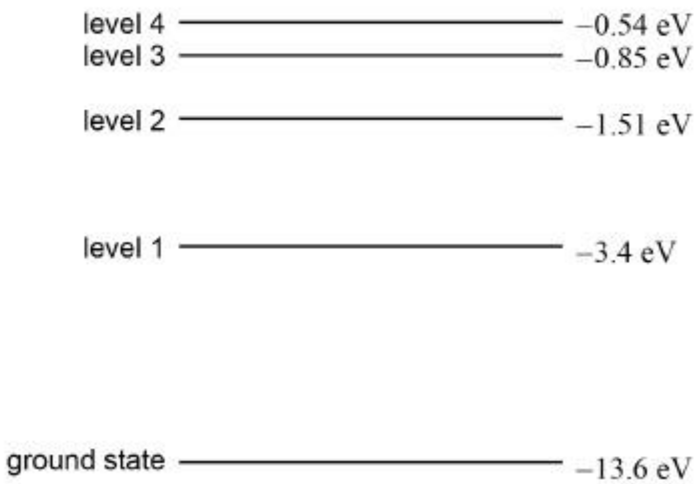
**(Total 1 mark)**

## Q15.

The diagram shows an energy level diagram for a hydrogen atom.

Electrons with energy 13.0 eV collide with atoms of hydrogen in their ground state.

What is the number of different wavelengths of electromagnetic radiation that could be emitted when the atoms de-excite?




**A** 0 ☐

**B** 3 ☐

**C** 6 ☐

**D** 7 ☐

**(Total 1 mark)**

## Q16.

(a) Describe what occurs in the photoelectric effect.

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**(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.

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**(2)**
**(Total 8 marks)**

## Q17.

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)**

## Q18.

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 ☐

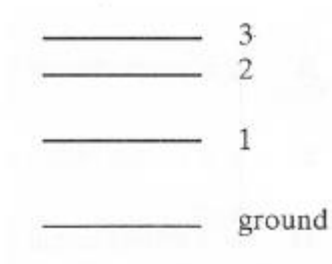
**(Total 1 mark)**

## Q19.

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 $6.2 \times 10^{14}$ Hz is emitted.

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

**A** $2.3 \times 10^{14}$ Hz

**B** $3.5 \times 10^{14}$ Hz

**C** $4.6 \times 10^{14}$ Hz

**D** $8.3 \times 10^{14}$ Hz

**(Total 1 mark)**

## Q20.

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

**A** electron diffraction by a crystalline material

**B** $\beta^-$ decay

**C** line spectra of atoms

**D** the photoelectric effect

**(Total 1 mark)**

## Q21.

Electromagnetic radiation incident on a metal surface can cause electrons to be emitted.

Which of the following statements is correct?

**A** Every photon incident on the surface causes an electron to be emitted.

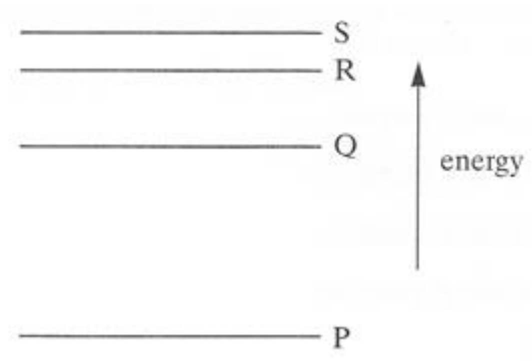
**B** All the emitted electrons have the same energy.

| | | |
|---|---|---|
| **C** | The range of energy of the emitted electrons depends on the intensity of the radiation. | ☐ |
| **D** | If the incident radiation is of a single frequency, the number of electrons emitted per second increases if the intensity of the radiation increases. | ☐ |

**(Total 1 mark)**

## Q22.

The diagram shows the four lowest energy levels for an electron in an atom. P, Q, R and S represent, to scale, the relative energy values of these energy levels.




An electron transition from level R to level Q is accompanied by the emission of a photon of visible light.

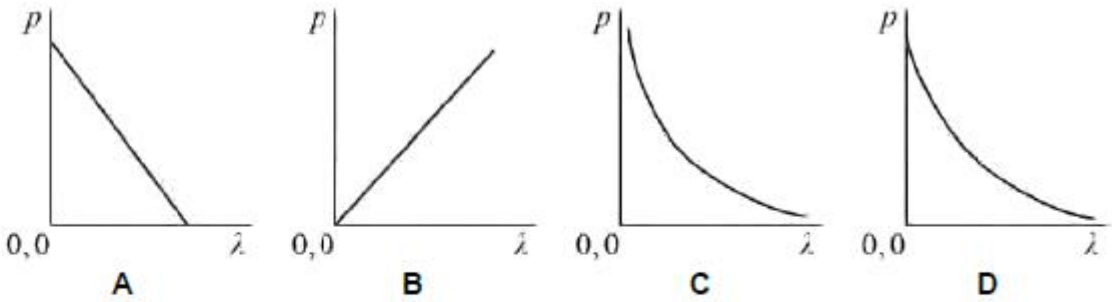
Which electron transition would be accompanied by the emission of a photon of infrared radiation?

| | | |
|---|---|---|
| **A** | S to R | ☐ |
| **B** | S to Q | ☐ |
| **C** | Q to P | ☐ |
| **D** | R to P | ☐ |

**(Total 1 mark)**

## Q23.

Which graph best shows the relationship between the momentum $p$ and the wavelength $\lambda$ for photons?




**A** ☐

**B** ☐

**C** ☐

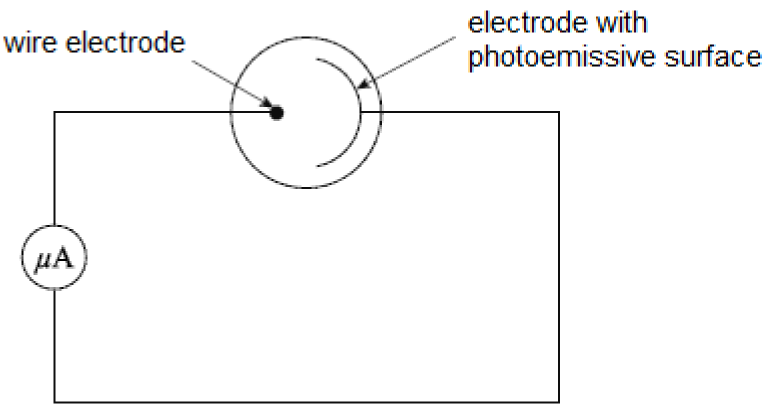
**D** ☐

**(Total 1 mark)**

## Q30.

**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.

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**(3)**

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

______________________________________________________________________

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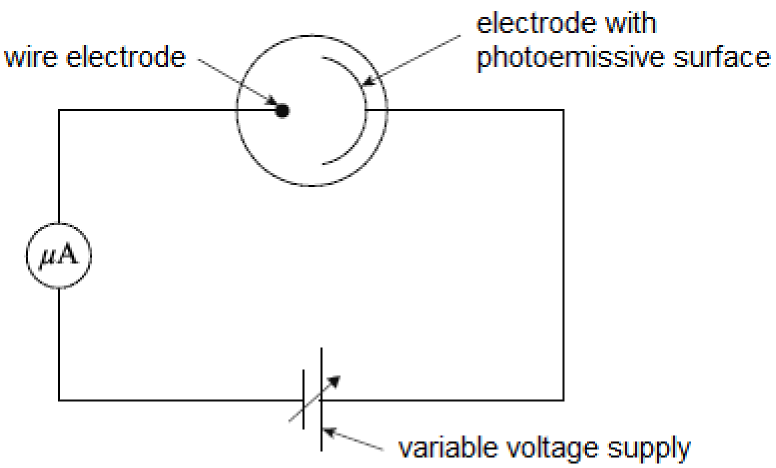
**(2)**

(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 $7.23 \times 10^{14}$ 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.

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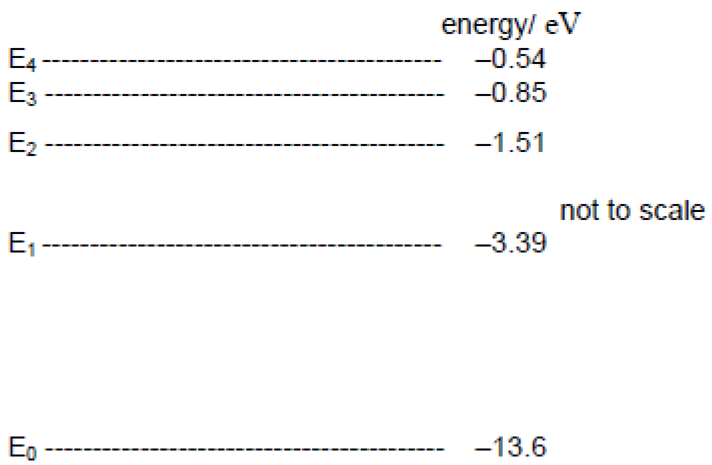
**(3)**

**(Total 12 marks)**

## Q31.

The diagram gives some of the energy levels of a hydrogen atom.




The transition of an excited hydrogen atom from $E_3$ to $E_1$ causes a photon of visible light to be emitted.

Which transition causes a photon of ultraviolet light to be emitted?

**A** $E_4$ to $E_3$ ⬭

**B** $E_3$ to $E_2$ ⬭

**C** $E_2$ to $E_1$ ⬭

**D** $E_1$ to $E_0$ ⬭

**(Total 1 mark)**

## Q32.

A proton moving with a speed $v$ has a de Broglie wavelength $\lambda$.

What is the de Broglie wavelength of an alpha particle moving at the same speed $v$?

**A** $\frac{\lambda}{4}$ ⬭

**B** $\lambda$ ⬭

**C** $2\lambda$ ⬭

**D** $4\lambda$ ⬭

**(Total 1 mark)**

## Q33.

(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.

______________________________________________

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**(3)**

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

______________________________________________

______________________________________________

(2)

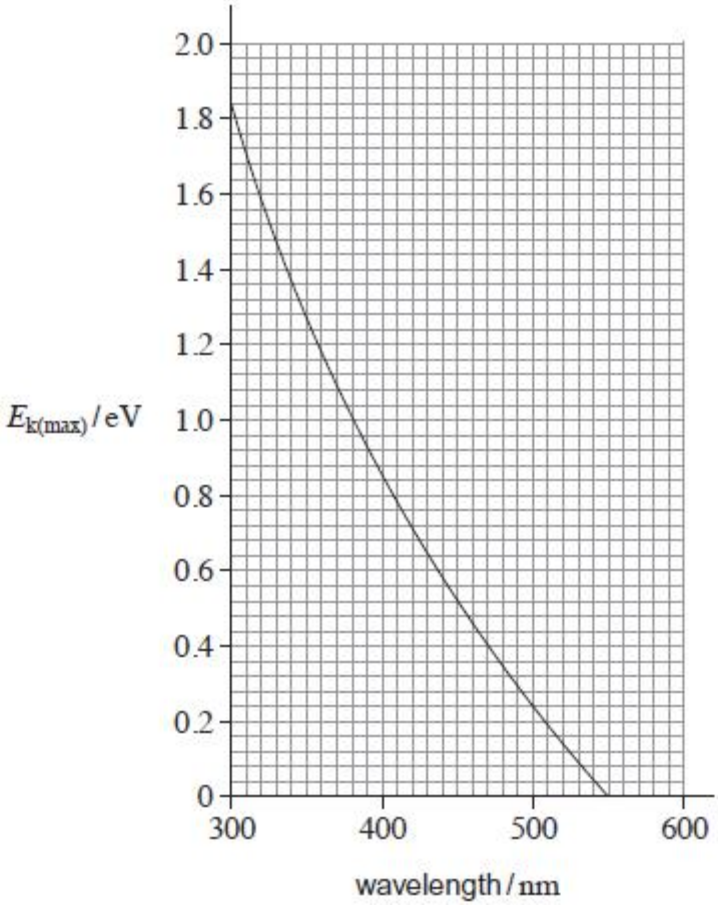
(b) Explain how the ultraviolet photons in the tube are converted into photons in the visible part of the electromagnetic spectrum.

(2)

**(Total 7 marks)**

## Q34.

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 $4 \times 10^{-19}$ 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 $4.6 \times 10^{5}$ m $s^{-1}$.

Determine the wavelength of the incident radiation.

wavelength ____________________ m

(3)

**(Total 8 marks)**

## Q35.

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 $1.2 \times 10^{15}$ 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).

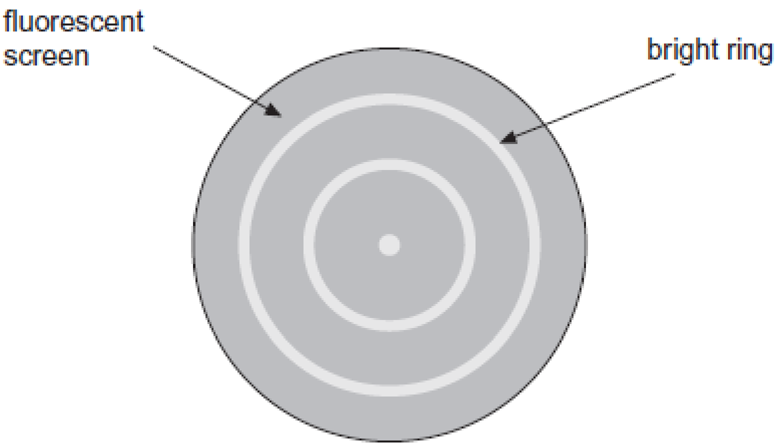
speed = ____________________ m $s^{-1}$

**(3)**

**(Total 12 marks)**

## Q36.

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.

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**(1)**

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

Calculate the de Broglie wavelength of the electrons.

de Broglie wavelength ____________________ m

**(2)**

**(Total 3 marks)**

## Q37.

Observations of the H-α line in the spectrum of a star indicate the presence of hydrogen. The H-α line has a wavelength of 656 nm and is produced by a transition of electrons into the −3.4 eV energy level.

Calculate the energy level that the electron moves from when emitting a photon corresponding to a wavelength of 656 nm. Give your answer in **J**.

energy level ____________________ J

**(Total 4 marks)**

## Q1.

(a)

| Transition | Ultraviolet | Visible | Infrared |
|---|---|---|---|
| A | | | ✓ |
| B | | ✓ | |
| C | ✓ | | |

*all correct 1 mark*

**1**

(b) EITHER
energy needed for electron to move to higher level/orbital ✓
OR
for a transition/excitation/change of levels an exact amount of energy is needed ✓
all the photon's energy absorbed( in 1 to 1 interaction) ✓
electron can transfer part of its energy (to cause a transition/excitation)/ continues moving/ lower kinetic energy/ lower speed ✓

*Any implication of photoelectric effect max 1*

*Accept one energy level to another*

**1**
**1**
**1**

(c) (use of $\varphi = hf_0$)
$\varphi = 6.63 \times 10^{-34} \times 5.1 \times 10^{14}$ ✓ (= $3.38 \times 10^{-19}$)
$\varphi = 3.38 \times 10^{-19}/1.6 \times 10^{-19} = 2.1(1)$ (eV) ✓
OR
$\varphi = 6.63 \times 10^{-34} \times 5.1 \times 10^{14}$ ✓(= $3.38 \times 10^{-19}$ )
energy in J $10.2 \times 1.6 \times 10^{-19} = 1.63 \times 10-18$ ✓
OR
energy levels in J = $10.2 \times 1.6 \times 10^{-19} = 1.63 \times 10^{-18}$ ✓
photons frequencies giving this energy= $2.46 \times 10^{15}$ ✓

*If see 2.1 get these first two marks*

**1**
**1**

$2 \rightarrow 1$ / C possible ✓

*Last mark dependent on previous 2*

**1**

(d) (use of hf = $\varphi + E_k$)
$12.1 \times 1.6 \times 10^{-19} = 2.1 \times 1.6 \times 10^{-19} + E_k$ ✓
$E_k = 1.6 \times 10^{-18}$(J) ✓
v = $\sqrt{(2 \times 1.6 \times 10^{-18}/9.11 \times 10^{-31})}$ ✓(= $1.9 \times 10^{6}$ m $s^{-1}$)

*Photoelectric equation must be used*

*Ecf for third mark their calculated kinetic energy having used photoelectric equation even if not converted eV to J or frequency to J*

*Correct answer gets ($1.9 \times 10^{6}$ m $s^{-1}$) full marks*

**1**
**1**

1

**[10]**

**Q2.**

**C**

**[1]**

**Q3.**

**D**

**[1]**

**Q4.**

**D**

**[1]**

**Q5.**

**C**

**[1]**

**Q6.**

(a) Clear indication of correct process

two correct values for $\lambda v$ from working plus conclusion

(7.35; 7.25; 7.35) ✓

three correct values plus conclusion ✓

*Condone no or misuse of powers of 10*

*Allow use of value of h as the constant to show that v values in table are consistent with the $\lambda$ values*

1

..........................................................................................

ratio approach $v_1/v_2 = \lambda_2/\lambda_1$ shown for 2 sets of data ✓

shown for two other sets of data + conclusion ✓

*May predict one of the values assuming inverse proportionality and compare with table value*

*(once for 1 mark; twice for 2 marks)*

1

(b) $h = \lambda mv$ or substitution of correct data in any form ✓

*May determine average value using mean constant from 2.1 or average 3 calculations in this part*

1

$6.7(0) \times 10^{-34}$ from first and third data set; $6.6(0) \times 10^{-34}$ from second ✓

1

(c) Particle behaviour would only produce a patch/circle of light /small spot of light or Particles would scatter randomly ✓

Wave property shown by diffraction/ interference ✓

Graphite causes (electron)waves/beam to spread out /electrons to travel in particular directions ✓

Bright rings/maximum intensity occurs where waves

interfere constructively/ are in phase ✓

for a diffraction grating maxima when sinθ = $n\lambda/d$ ✓

*Marks are essentially for*
*1. Explaining appearance of screen if particle*
*2. Identifying explicitly a wave property*
*3. Explaining what happens when diffraction occurs*
*4. Explaining cause of bright rings*
*5. Similar to diffraction grating formula (although not same)*
*NB Not expected: For graphite target maxima occur when sinθ =$\lambda/2d$ (d =spacing of atomic layers in crystal)*

**1**
**1**
**1**

(d) Electrons must provide enough (kinetic) energy

'instantly' to cause the excitation

**OR**

the atom or energy transfer in 1 to 1 interaction

**OR**

electron can provide the energy in discrete amounts

**OR**

energy cannot be provided over time as it would be in a wave

*Description of Photoelectric effect = 0*
*Not allowed: any idea that wave cannot pass on energy, e.g. waves pass through the screen*

**1**

**Any 2 from**

Idea of light emission due to excitation and de-excitation of electrons/atoms ✓

Idea of collisions by incident electrons moving electrons in atoms between energy levels/shells/orbits ✓

Light/photon emitted when atoms de-excite or electrons move to lower energy levels ✓

**1**

1

**[10]**

## Q7.

**B**

**[1]**

## Q8.

**A**

**[1]**

## Q9.

3rd box

(Electrons produe dark rings in diffraction experiments) ✓

**[1]**

## Q10.

(a) $\lambda$ = 656 nm ✓

*Power of 10 error allow 2*

Use of $E=hc/\lambda$ ✓ = 3.0 × $10^{-19}$ (J)

*Allow ecf for wrong choice of wavelength*

*E*/ 1.6 × $10^{-19}$

= 1.9 (1.88) (allow 1sf if correct)

*Treat as skill mark – allow conversion for any value of E*

3

(b) They are (just) free ✓

*Allow released from atom*

1

(c) This is the ground state ✓

or

This is the lowest level an electron can occupy

*Allow lowest energy state*

*Condone level for state*

*Allow description of ground state*

1

(d) To become free / to remove an electron (reach zero energy) energy has to be supplied ✓

or

Energy decreases from 0 as electrons move to lower energy levels/relate to energy needed to move from that state to 0

*Or*

*Electrons release energy as they move lower*

*Or*

*Zero is the maximum energy*

**1**

(e) **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 |
|---|---|
| 6 | All three aspects analysed. 6 marks can be awarded even if there is an error and/or parts of one aspect missing. |
| 5 | A fair attempt to analyse all 3 aspects. If there are a couple of errors or missing parts then 5 marks should be awarded. |
| 4 | Two aspects successfully discussed, or one discussed and two others covered partially. Whilst there will be gaps, there should only be an occasional error. |
| 3 | Two aspects discussed, or one discussed and two others covered partially. There are likely to be several errors and omissions in the discussion. |
| 2 | Only one aspect discussed successfully, or makes a partial attempt at 2 or all 3. |
| 1 | None of the three aspects covered without significant error. |
| 0 | No relevant analysis. |

*The following statements are likely to be present.*

***A Reason for high potential difference***

*pd accelerates electrons/produces high speed / high energy electrons in the tube L1*

*electrons have to have sufficient energy to excite the atoms/raise electrons into higher levels L3*

***B Relation between spectrum and energy level diagram***

*Visible spectrum results from excited electrons moving into the lower level at -3.4 eV L3*

*Each transition results in a photon of light L2*

*Energy of photon is the difference in the energies of the two levels L2*

*Frequency of light in the spectrum given by* $\Delta E = hf$ *L1*

***C Relevant calculation clearly communicated***

*Gives an example: eg the lowest frequency is due to a transition from the -1.5 eV level to the -3.4 level L1*

*Uses an energy difference to deduce one of the wavelengths: eg energy difference in J =* $3 \times 10^{-19}$ *L2*

*$\lambda = hc/E = 660$ nm L2*

6

**[12]**

## Q11.

**C**

**[1]**

## Q12.

**A**

**[1]**

## Q13.

**D**

**[1]**

## Q14.

**C**

**[1]**

## Q15.

**C**

**[1]**

## Q16.

(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 = $hc / \lambda$ condone errors in powers of 10✓

$5.2 \times 10^{-19}$J✓

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

photon energy = 3.3 eV or work function = $3.7 \times 10^{-19}$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]**

## Q17.

D

**[1]**

## Q18.

D

**[1]**

## Q19.

C

**[1]**

## Q20.

A

**[1]**

## Q21.

D

**[1]**

## Q22.

A

**[1]**

## Q23.

C

**[1]**

## Q30.

(a) energy of photon ✓ 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]**

## Q31.

D

**[1]**

## Q32.

A

**[1]**

## Q33.

(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]**

## Q34.

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

2

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

3

(b) $E_k = 9.6 \times 10^{-20}$
J converted to eV / 0.6 eV
4.35 to $4.40 \times 10^{-7}$ (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 $4.6 \times 10^{-19}$ using calculated value
or $f = 7.5 \times 10^{14}$(Hz)

$4 \times 10^{-7}$ to $4.4 \times 10^{-7}$ (m)

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

3

**[8]**

## Q35.

(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 $hf = eV$)

$6.63 \times 10^{-34} \times f = 5.15 \times 1.60 \times 10^{-19}$✓

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

*if no working and $1.24 \times 10^{15}$(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 $1.2 \times 10^{15}$ 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 $c = f\lambda$ )

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

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

$v = 3010$ m $s^{-1}$✓✓

*first mark minimum working – determination of wavelength*

*bald answer gets 2 marks*

*range to 3 sig figs 2900 – 3030*

3

**[12]**

## Q36.

(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

$2.1 \times 10^{-11}$ (m)

A1

2

**[3]**

## Q37.

Correct substitution ignoring powers of 10 in $hc / \lambda$

C1

Photon energy = 3.0(3) × $10^{-19}$J

*Photon energy in eV = 1.9 eV gets 3 marks*

A1

Conversion of −3.4 eV to J (5.44 × $10^{-19}$ seen)

C1

Answer −2.4 × $10^{-19}$ J (must have negative sign)

*−8.4(8.5) × $10^{-19}$ J gets 3 marks*

A1

**[4]**

## Q1.

This question assessed the understanding of excitation and ionisation and also the photoelectric effect.

(a) This objective question was correctly answered by the majority of students (66%).

(b) This question produced very good discrimination. Many students were able to explain satisfactorily that an exact amount of energy was needed to excite an electron to a higher energy level. Linking this to why the photon needed an exact amount of energy, whereas the free electron only needed a minimum, was more challenging. The idea that all the photon's energy was absorbed was better understood than the reason why the incident electron only needed a minimum energy. It was common to see answers that made correct statements but then went on to include a discussion of the photoelectric effect. Nearly 40% of students gained no credit.

(c) This question was well done with nearly half the students scoring full marks.

(d) Performance in this multi-step calculation was disappointing, with over half the students failing to score any marks. The photoelectric equation did seem well known but substitution was a real issue for many. Students had to extract data from different sources and this clearly caused them problems. A common error was a failure to convert the photon energy to joule.

## Q2.

Most students (67.8%) were able to relate this gradient to the $hc$.

## Q3.

Most students (64.8%) were able to select the correct answer, with distractor A being the most common wrong answer. These students did not take into account that the visible photon has a smaller energy than the ultraviolet photon.

## Q4.

Students were less confident with this question, with less than 38.8% selecting the correct answer. B and C were often selected as the answer, with students demonstrating limited ability to re-arrange the de Broglie equation in the required manner.

## Q5.

This question had a very high success rate with 84.2% of students able to recall the physical properties exhibited in the photoelectric effect and electron diffraction.

## Q6.

(a) This was often well answered (63% of students gained both marks), although presentation of the work left much to be desired in many instances. Conclusions were often vague or non-existent (e.g. a series of ticks), rather than a convincing statement. Questions of this type are quite common in examinations and a provide a useful skill in testing practical data. Using a 'known' equation and data to demonstrate that the numbers are compatible is not an acceptable approach.

(b) For full credit in this part it was necessary to provide some evidence of working. It was well done by a majority of the students; over 80% scored two marks.

(c) The fact that diffraction or interference is a wave property and explaining how wave theory explains the bright rings were the two most common points made. To gain full credit, either an explanation of what would be seen if electrons behaved as particles or an explanation of what is meant by diffraction and where it occurred was required. Neither of these was commonly seen in students' responses.

(d) Most answers missed the point of the question. There were many responses that explained the excitation and de-excitation process, some in much detail, but did not explain clearly that the energy transfer to excite the electron in the atom has to occur with an exact amount of energy being supplied to the electron instantaneously. Many students quoted a 'one to one interaction', but this seemed to be a learned response and provided insufficient evidence of them understanding what this means.

## Q7.

68.6% correct

## Q8.

76.5% correct

## Q9.

Students should be reminded to make it clear which answer they have chosen, and to avoid putting marks in more than one box. It was very accessible, with over 70% obtaining the mark.

## Q10.

This question gave students the opportunity to demonstrate their knowledge and understanding of photons and energy in the context of a discharge tube. There was much evidence of confusion with the more commonly tested fluorescent tube.

(a) Difficulties choosing the correct wavelength proved to be an obstacle for many students. The award of the final mark was made without reference to the method. Some credit was also awarded for students who made an error calculating the energy. The conversion to eV proved difficult for some who decided to multiply rather than divide by the charge on the electron.

(b) Many students found it difficult to describe the 'free' energy state and it is clear that this is not an idea that is commonly discussed. Furthermore, many students had difficulties interpreting an energy diagram with the zero at the top. It was common to see this energy level referred to as the ground state because of this.

(c) Problems with the 'upside-down' scale persisted into this question, although a greater percentage of students was able to identify the ground state.

(d) It was common to see the negative charge on the electron being given as the reason for negative energy values. Other answers failed to get the mark if they were poorly expressed so that it was unclear what was happening in terms of energy.

(e) Despite the extended writing question being the last on the paper, there was no indication that students ran out of time or space. Generally, attempts to explain the reason for high potential difference were often vague so that electrons being accelerated and those within the atoms became confused. On the whole, better attempts were made to link the spectrum and energy level diagrams. Several students used previously analysed data to help answer the final part of this question. Common errors were seen with the introduction of the photoelectric effect or fluorescent tube into the answer.

## Q11.

The most frequently selected distractor was B, accounting for 30% of the responses. It would benefit students to emphasise that the maximum kinetic energy depends only on the frequency of the incident radiation and the work function of the metal surface. Increasing the power, without changing the frequency, will only increase the number of photons incident on the surface every second, and will not increase the energy each photon carries. It would have had to have been clearly stated that the frequency had been doubled as a means of doubling the power for distractor B to have been the answer.

## Q12.

This question was little more than recall of the features of the graph of maximum kinetic energy against frequency of incident radiation. Over 60% of students correctly selected the correct answer.

## Q13.

Just over 50% of students got this question correct. Distractors B and C were the most commonly selected incorrect answers. Students should be aware of how to plot linear graphs for equations in the form $y=k/x$.

## Q30.

Answers given to this question on the photoelectric effect provided evidence of the tendency of some students to not present full arguments when applying physics principles. In part (a) most students identified that electrons needed to leave the surface but the linking of this to the frequency of the radiation was quite vague. Responses that failed to mention photons were common and many did not emphasise the importance of the work function. It was not unusual to see discussions that confused the photoelectric effect with the excitation and ionisation of electrons in individual atoms. It was a similar story in (b) where the majority of students realised that the current would increase but then failed to explain why in terms of the increased number of photons striking the metal surface per second. The calculation in part (c) was generally well done with nearly three-quarters of students scoring full marks. Surprisingly, far fewer were then able to use their correct answer from (c) to calculate the stopping potential in (d). Part (e) was another example of incomplete arguments. The majority did appreciate that the stopping potential would increase but were unable to give complete explanations for this effect. Better responses did link this increase to maximum kinetic energy but it was very rare to see answers explaining that this was due to greater energy transfer by photons.

## Q31.

Approximately two thirds of students spotted that a bigger energy jump was needed to produce a photon of UV, and therefore chose D. Distractors A (the smallest energy jump) and C (the next smallest) were chosen by a similar number of students who failed to make the link between energy and frequency perhaps.

## Q32.

Multiple choice questions involving the algebraic manipulation of an equation, rather than the use of data, are fairly common. 62% of students were able to see that the alpha particle would have four times the mass, therefore four times the momentum, and one quarter of the wavelength. The most popular distractor, D, was chosen by students who missed out the last step, perhaps. C was also a common incorrect answer, perhaps chosen by students who thought that the fact alpha particles contain two protons was significant.

## Q33.

Part (a)(i) was done well with almost 60 % of students achieving full marks. Many answers seen were of a good standard with students choosing their words carefully to effectively communicate the positions of the relevant electrons and each stage in the process. Students who fared less well simply stated the mercury atom became excited without detailing how this affected electrons within the atom. Other students were unaware of the process that led to the energy transfer with lots of students stating that it was due to absorption of a photon rather than an electron-electron collision. Part (a)(iii) was only completed to the desired standard by the most able of the students. Weaker responses stated that the energy emitted was lower in relaxation even though quite often the same energy level transition was quoted (ground to excited to ground). Higher achieving students communicated the idea that the transitions in relaxation were between closer lying energy levels resulting in a lower frequency photon being emitted.

## Q34.

(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 minimum energy required and that it refers to electrons at the surface.

(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.

## Q35.

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 $1.2 \times 10^{15}$ 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 $1.2 \times 10^{15}$ 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.

## Q36.

(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.

## Q37.

Many were successful in obtaining the energy of the emitted photon and / or were able to convert 3.4 eV to J. Calculating the energy of the initial energy level proved more of a problem and there were many answers with the correct numerical value but no negative sign or answers where candidates calculated the energy level the electron would have to move into rather than from.