Volume

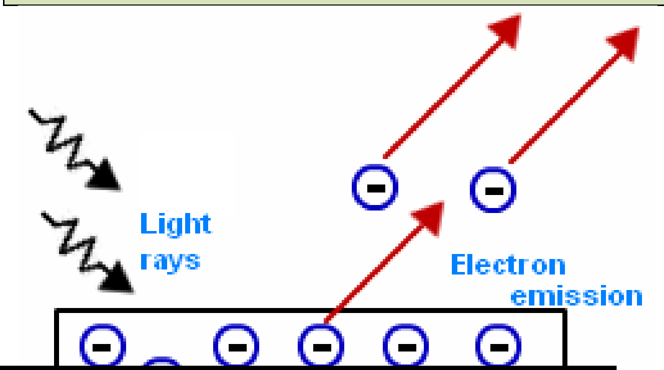
Two

ST MARY’S SCIENCE DEPARTMENT:

PHYSICS

A LEVEL PHYSICS **YEAR 1**
STUDENT INDEPENDENT WORK BOOK
PARTICLES AND RADIATION
3.2.2: ELECTROMAGNETIC RADIATION

NAME	
PHYSICS CLASS	
MODULE TEACHER	
ALPS GRADE	



A-LEVEL PHYSICS

TOPIC 2

INDEPENDENT WORK BOOK

THIS MUST BE BROUGHT TO ALL PHYSICS LESSONS.

Contents

Overview

This section introduces students both to the fundamental properties of matter, and to electromagnetic radiation and quantum phenomena. Through a study of these topics, students become aware of the way ideas develop and evolve in physics. They will appreciate the importance of international collaboration in the development of new experiments and theories in this area of fundamental research.

IMPORTANT NOTE

This book contains all of the activities you can carry out independently in your study periods to enhance your understanding in A-Level Physics.

You may work through the activities in this book and mark this work yourself. You work will then be reviewed by your teacher in KS5 file checks. This work is in addition to the class work and homework you carry out.

This book may also be used as a revision resource for intervention, internal assessments and external assessments.

Please keep this in your student file.

As part of this course you are expected to **read through this preparatory reading book** and **complete the independent study tasks**.

This work will not be assessed but will be monitored by your class teacher.

This must be completed by the deadline set by your class teacher.

SECTION 1

INDEPENDENT STUDY TASK

Instructions

Read through the information from the student preparatory book and then produce revision posters on the key points highlighted on the following pages.

These notes should be used as a revision resource for assessments.

INDEPENDENT STUDY TASK 1

Produce an **information sheet** on Photon Theory.

This is an independent study task to carried out outside of lesson.

INDEPENDENT STUDY TASK 2

Produce an **information sheet** on the Photoelectric Effect.

This is an independent study task to carried out outside of lesson.

INDEPENDENT STUDY TASK 3

Produce an **information sheet** on excitation and ionisation.

This is an independent study task to carried out outside of lesson.

INDEPENDENT STUDY TASK 4

Produce an **information sheet** on wave-particle duality.

This is an independent study task to carried out outside of lesson.

SECTION 2

KNOWLEDGE CHECKER

Instructions

Read through the information from the student preparatory book and then answer the following questions from the different parts of the topics.

These questions are designed to introduce the different parts of this module.

Use the mark schemes to review your knowledge and understanding.

QUESTIONS

Use the preparatory reading notes to answer these questions.

A1. Explain what the photoelectric effect is.

[1 Mark]

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A2. What is meant by the work function of a metal?

[1 Mark]

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A3. How is the maximum kinetic energy of a photoelectrons related to the work function?

[1 Mark]

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A4. Explain what is meant by the stopping potential.

[1 Mark]

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A5. An electron hits a hydrogen atom in its ground state and excites it. What does this mean?

[1 Mark]

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A6. What observations show light to have a 'wave-like' character?

[1 Mark]

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A7. What observations show light to have a 'particle-like' character?

[1 Mark]

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Use the preparatory reading notes to answer these questions.

ADVANCED SECTION

Use the preparatory reading notes to answer these questions.

A8. An isolated zinc plate with neutral charge is exposed to high frequency ultraviolet light. State and explain the effect of the ultraviolet light on the charge of the plate.

[1 Mark]

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A9. Explain why photoelectric emission from a metal surface only occurs when the frequency of the incident radiation exceeds a certain threshold value.

[1 Mark]

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A10. Calculate the momentum of an electron with a de Broglie wavelength of 590nm.

[1 Mark]

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Use the preparatory reading notes to answer these questions.

Use the preparatory reading notes to answer these questions.

Questions **A11-A12** refer to the following statement.
An electron is accelerated through a potential difference of 12.1eV.

A11. How much kinetic energy does the electron gain in eV?

[1 Mark]

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A12. How much kinetic energy does the electron gain in joules?

[1 Mark]

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Use the preparatory reading notes to answer these questions.

ANSWERS

A1. Explain what the photoelectric effect is.

[1 Mark]

The instantaneous emission of electrons from the surface of a metal when electromagnetic radiation is absorbed by the metal surface.

A2. What is meant by the work function of a metal?

[1 Mark]

The minimum energy needed to release electrons from the metal surface.

A3. How is the maximum kinetic energy of a photoelectrons related to the work function?

[1 Mark]

The higher the work function, the lower the maximum kinetic energy of the photoelectrons.

A4. Explain what is meant by the stopping potential.

[1 Mark]

The potential difference required to produce enough electrical potential energy to stop the emitted electrons from moving.

A5. An electron hits a hydrogen atom in its ground state and excites it. What does this mean?

[1 Mark]

Excitation is when an electron moves to a higher energy level without leaving the atom.

A6. What observations show light to have a 'wave-like' character?

[1 Mark]

Diffraction
Polarisation
Interference

A7. What observations show light to have a 'particle-like' character?

[1 Mark]

Photoelectric Effect
Line Spectra

ADVANCED SECTION

A8. An isolated zinc plate with neutral charge is exposed to high frequency ultraviolet light. State and explain the effect of the ultraviolet light on the charge of the plate.

[1 Mark]

The plate becomes positively charged.
Negative electrons in the metal absorb energy from the UV light and leave the surface.

A9. Explain why photoelectric emission from a metal surface only occurs when the frequency of the incident radiation exceeds a certain threshold value.

[1 Mark]

An electron needs to gain a certain amount of energy before it can leave the surface of the metal. If the energy carried by each photon is less than this work function, no electrons will be emitted.

A10. Calculate the momentum of an electron with a de Broglie wavelength of 590nm.

[1 Mark]

$p = h/\lambda = 6.63 \times 10^{-34} / 590 \times 10^{-9} = 1.1 \times 10^{-27}$ kg ms^{-1}

Questions **A11-A12** refer to the following statement.
An electron is accelerated through a potential difference of 12.1eV.

A11. How much kinetic energy does the electron gain in eV?

[1 Mark]

E = V = 12.1eV

A12. How much kinetic energy does the electron gain in joules?

[1 Mark]

$E = eV \times 1.60 \times 10^{-19} = 12.1 \times 1.60 \times 10^{-19}$
$E = 1.94 \times 10^{-18}$J

SECTION 3

QUESTIONS

Instructions

Read through the information from the student preparatory book and then answer the following questions from the different parts of the topics.

Use the mark schemes to review your knowledge and understanding.

TOPIC: 3.2.2.1: The Photoelectric Effect
SPEC CHECK

Specification	Completed?
Threshold frequency; photon explanation of threshold frequency.	
Work function ϕ, stopping potential	
Photoelectric equation: $h f = \phi + E_k$ (max) E_k (max) is the maximum kinetic energy of the photoelectrons.	
Demonstration of the photoelectric effect using a photocell or an electroscope with a zinc plate attachment and UV lamp.	

SUPPORT ACTIVITY

The photoelectric effect is the emission of electrons from a metal surface when light is incident on the surface. Emission only takes place if the frequency f of the incident light is greater than a minimum value, referred to as the **threshold frequency**.

Light is composed of packets of energy called **photons**. Einstein explained the photoelectric effect by assuming a single electron in the metal, at or near its surface, absorbs a photon and gains sufficient energy to escape from the metal. He said that:

The energy of a photon of frequency f is given by $E = hf$, where f is the frequency of the incident light and h is the Planck constant

There is a *minimum* amount of energy, the **work function φ**, of the metal needed by an electron to escape from the metal surface.

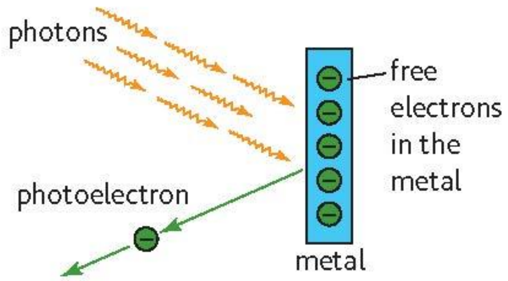

Figure 1 Explaining the photoelectric effect

An electron that absorbs a photon gains energy hf from the photon.

If the electron is **at** the surface when it absorbs the photon, its kinetic energy after escaping is equal to $hf - \varphi$.

If the electron is **below** the surface when it absorbs the photon, it needs to use some of its energy to reach the surface. It then needs to use energy equal to φ to escape from the surface. So its kinetic energy after escaping is less than $hf - \varphi$.

Therefore, the kinetic energy of an emitted electron cannot be greater than $hf - \varphi$. Hence Einstein's photoelectric equation for the maximum kinetic energy of a photoelectron is $KE_{max} = hf - \varphi$.

Questions

For these questions, use the values: $c = 3.00 \times 10^{8}\ \text{m s}^{-1}$ and $h = 6.63 \times 10^{-34}\ \text{J s}$.

1. The following events involving an electron and a photon take place when photoelectric emission occurs. Place the events in the correct order. **[2 Marks]**

A The electron does work to leave the metal surface.

B The photon is absorbed.

C The electron gains energy.

D The electron uses energy to reach the surface.

E The photon arrives at the metal surface.

2.1 State what is meant by the work function of a metal.

[1 Mark]

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2.1 Explain why photoelectric emission from a certain metal surface **cannot** occur if the frequency of the incident light is less than a certain value that depends on the work function of the metal.

[4 Marks]

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3. Photoelectric emission takes place when light of wavelength 550 nm (550×10^{-9} m) is incident on a metal surface that has a work function of 1.75×10^{-19} J.

3.1 Calculate the frequency and the energy of an incident photon.

[2 Marks]

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3.2 Calculate the maximum kinetic energy of an emitted electron.

[1 Mark]

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4. A photocell contains a metal surface which will eject electrons when it is exposed to light of suitably high frequency. In an experiment, the photocell is placed in a darkened room, and connected in series with a sensitive ammeter. The ammeter registers a current when light of wavelength 450 nm (450×10^{-9} m) is incident on the photocathode inside the photocell.

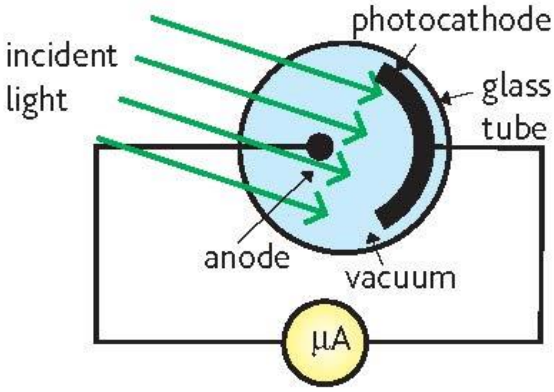

Figure 2 Using a vacuum photocell

4.1 The intensity of a light source is a measure of the energy it provides each second to the surface. Explain why the current increases when the light intensity of the incident light is increased.

[3 Marks]

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4.2 The maximum kinetic energy of the electrons emitted in the photocell is 1.8×10^{-19} J.
Show that the work function of the metal is 2.6×10^{-19} J.

[3 Marks]

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5. The table below gives the work function of five metals. The table also shows the threshold frequency of light incident on two of the metals.

Metal	Work Function / 10^{-19} J	Threshold Frequency / 10^{14} Hz
caesium	3.4	5.1
calcium	4.6	6.9
cadmium	6.5	
zinc	6.9	
selenium	8.2	

5.1 Calculate the threshold frequency for light incident on cadmium, zinc and selenium.

[3 Marks]

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5.2 Which metals will emit electrons when light of wavelength 430 nm is incident on their surface? Explain your answer.

[2 Marks]

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5.3 Calculate the maximum kinetic energy of an electron emitted from caesium when light of wavelength 430 nm is incident on its surface.

[2 Marks]

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5.3 A light source emits a range of wavelengths from 300 nm to 650 nm.
Which metals will not give photoelectric emission with this light source? Explain your answer.

[4 Marks]

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ANSWERS

1. Award *2 marks* for the correct order.

E The photon arrives at the metal surface.

B The photon is absorbed.

C The electron gains energy.

D The electron uses energy to reach the surface.

A The electron does work to leave the metal surface.

2.1 The work function of a metal is the minimum energy needed by an electron to escape from the surface of a metal. (*1 mark*)

2.2 Light consists of photons which each have energy hf, where f is the light frequency and h is the Planck constant (*1 mark*). Photoelectric emission is the emission of electrons from a metal surface when light is directed at the surface (*1 mark*). A conduction electron in the metal that absorbs a photon of energy hf cannot leave the surface if the energy it gains is less than the work function φ of the metal (*1 mark*). Thus, if the frequency of the incident light is less than φ/h, the electron cannot leave the metal (*1 mark*).

3.1

$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8}{550 \times 10^9} = 5.45 \times 10^{14}$ Hz (*1 mark*)

Photon energy, $hf = 6.63 \times 10^{-34} \times 5.45 \times 10^{14} = 3.62 \times 10^{-19}$ J (*1 mark*)

3.2 Maximum kinetic energy = $hf - \phi = 3.62 \times 10^{-19} - 1.75 \times 10^{-19} = 1.87 \times 10^{-19}$ J (*1 mark*)

4.1 Each photon incident on the photocathode can supply enough energy to a conduction electron to enable the electron to escape (*1 mark*). Increasing the intensity increases the number of photons per second incident on the photocathode (*1 mark*). So, the number of electrons that escape each second increases and therefore the ammeter reading increases (*1 mark*).

4.2

For an incident photon, $f = \frac{c}{\lambda} = \frac{3.00 \times 10^8}{450 \times 10^9} = 6.67 \times 10^{14}$ Hz (*1 mark*)

Photon energy, $hf = 6.63 \times 10^{-34} \times 6.67 \times 10^{14} = 4.42 \times 10^{-19}$ J (*1 mark*)

Since the maximum kinetic energy = photon energy − the work function, φ,

φ = photon energy − maximum kinetic energy = $4.4(2) \times 10^{-19} - 1.8 \times 10^{-19} = 2.6 \times 10^{-19}$ J (*1 mark*)

5.1 Award *1 mark* for each correct answer (in bold in the table).

metal	work function / 10^{-19} J	threshold frequency / 10^{14} Hz
caesium	3.4	5.1
calcium	4.6	6.9
cadmium	6.5	**9.8**
zinc	6.9	**10.4**
selenium	8.2	**12.4**

5.2

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8}{430 \times 10^9} = 6.98 \times 10^{14}\ \text{Hz}$$

Therefore, only caesium and calcium will emit electrons (*1 mark*) with light of this wavelength as the light frequency is greater than their threshold frequencies (*1 mark*).

5.3 The energy of a 430 nm photon = $hf = 6.63 \times 10^{-34} \times 6.98 \times 10^{14} = 4.63 \times 10^{-19}$ J. (*1 mark*)
Therefore, the maximum kinetic energy of an electron emitted from caesium
= $hf - \phi = 4.6(3) \times 10^{-19} - 3.4 \times 10^{-19} = 1.2 \times 10^{-19}$ J. (*1 mark*)

5.4

For 300 nm light, $f = \frac{c}{\lambda} = \frac{3.00 \times 10^8}{300 \times 10^{-9}} = 10.0 \times 10^{14}$ Hz (*1 mark*)

For 650 nm light, $f = \frac{c}{\lambda} = \frac{3.00 \times 10^8}{650 \times 10^{-9}} = 4.62 \times 10^{14}$ Hz (*1 mark*)

Therefore, zinc and selenium will not emit electrons with this light source (*1 mark*) as their threshold frequencies are greater than the upper frequency of the source's frequency range (*1 mark*).

SUBJECT KNOWLEDGE

To build your subject knowledge, answer the following questions.

WARNING: The answers are not found in this guide.

Q1. Explain what the photoelectric effect is.

Q2. What three conclusions were drawn from experimentation on the photoelectric effect?

Q3. What is meant by the work function of the metal?

Q4. How is the maximum kinetic energy of a photoelectron related to its work function?

Q5. Explain what is meant by stopping potential. Write down the stopping potential formula.

CHALLENGE QUESTION

To assess your understanding, answer the following higher-level question on this topic.

1. Einstein derived the following equation to explain the photoelectric effect:
hf = φ + KEmax
Define the following terms from the equation
1.1 hf

[1 Mark]

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1.2 φ

[1 Mark]

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Electromagnetic radiation of frequency 1.2×10^{15} Hz is incident on the surface of a negatively charged aluminium plate. The work function of aluminium is 4.1 eV.
1.3 Show that the maximum speed of the electrons emitted from the surface of the aluminium is 5.5×10^{5} m $^{s-1}$.

[4 Marks]

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1.4 State and explain what change, if any, occurs to the maximum speed of the emitted electrons when the intensity of the electromagnetic radiation is increased.

[2 Marks]

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1.5 Moving electrons have wave-like properties.
Calculate the de Broglie wavelength λ for electrons travelling at 5.5×10^5 m s^{-1}.

[2 Marks]

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λ = ... m

MARK SCHEME

Question	Answer	Marks	Guidance
1.1	Energy of a photon	B1	**Ignore** *h* is Planck constant and *f* is frequency
1.2	Minimum energy required to remove/emit (a single) electron from the metal surface	B1	**Ignore** 'it is work function' **Ignore** photoelectric effect
1.3	4.1 eV = = 4.1 × 1.6 × 10^{-19} or 6.56 × 10^{-19} J OR $E_k = 6.63 \times 10^{-34} \times 1.2 \times 10^{15} - \phi$	C1	**Allow** $f_0 = 9.9 \times 10^{14}$ Hz
	$E_k = 6.63 \times 10^{-34} \times 1.2 \times 10^{15} - 6.56 \text{ x } 10^{-19}$	C1	**Allow** $E_k = 6.63 \times 10^{-34} \times (1.2 \times 10^{15} - 9.9 \text{ x } 10^{14})$
	$E_k = 1.39 \times 10^{-19}$J	C1	**Allow** 1.4 × 10^{-19} J
	$v = \sqrt{\dfrac{2 \times 1.39 \times 10^{-19}}{9.11 \times 10^{-31}}} = \sqrt{3.06 \times 10^{11}}$	C1	3.06×10^{11} scores three marks
	5.536 × 10^{5} m s^{-1}	A0	
1.4	Maximum energy is independent of intensity/(number of photons has increased but) energy of photon is the same/energy of a photon is only dependent on frequency/intensity affects the number of photons/electrons released only/frequency of photon has not changed	M1	
	No change in maximum speed	A1	**Not** "Does not increase"
1.5	$\lambda\left(=\dfrac{h}{mv}\right) = \dfrac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 5.5 \times 10^{5}}$	C1	
	$= 1.3(2) \times 10^{-9}$ (m)	A1	
	Total	**10**	

CHALLENGE QUESTION

To assess your understanding, answer the following higher-level question on this topic.

1. In an experiment to demonstrate the photoelectric effect, electromagnetic waves are incident on a silver surface.
Fig. 6 shows the variation with frequency f of the maximum kinetic energy KE_{max} of the photoelectrons.

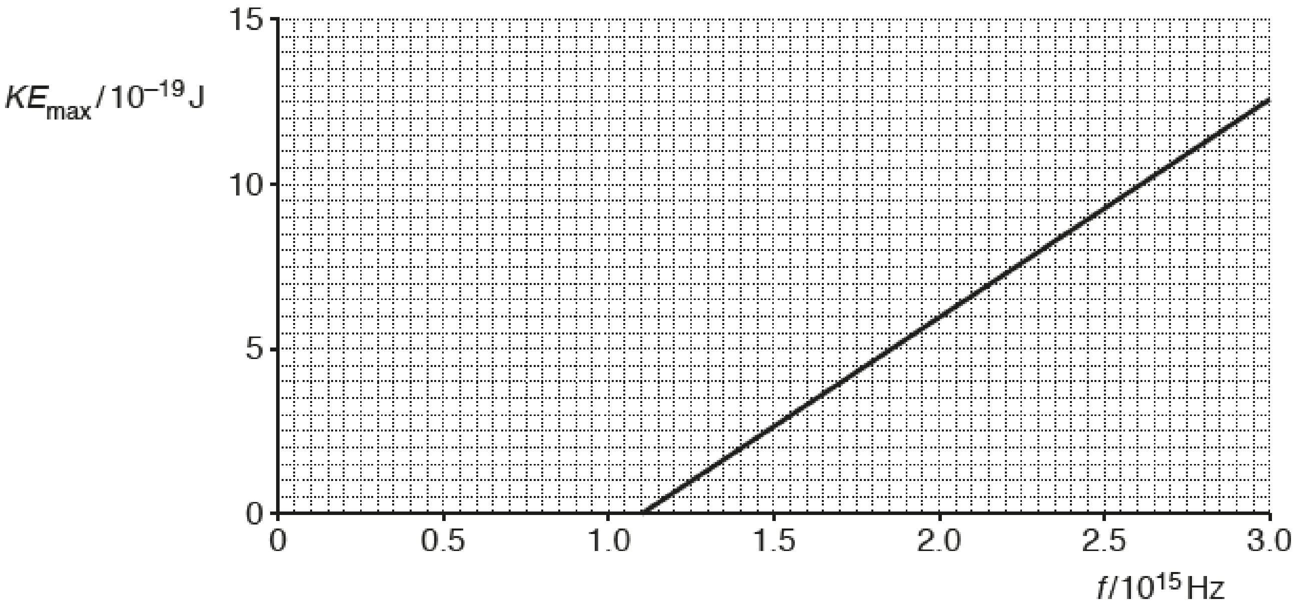

Fig. 6

1.1 Define the term threshold frequency.

[1 Mark]

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1.2 Use **Fig. 6** to state the threshold frequency f_0 for silver.

[1 Mark]

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f_0 .... Hz

1.3 Use your answer in **1.2** to calculate the work function φ of silver.
Give your answer in electron volt (eV).

[2 Marks]

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φ = ... eV

1.4 Electrons can behave as a wave.
Describe the behaviour of electrons which demonstrates that they have wave properties.

[4 Marks]

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MARK SCHEME

Question	Answer	Marks	Guidance
1.1	Threshold frequency is the minimum frequency (of the incident EM waves/photon) to detach / emit / remove / release an electron (from the surface of the silver)	B1	**Allow** electrons **Allow** photoelectron / photoelectrons
1.2	$1.1(0) \times 10^{15}$ (Hz)	B1	
1.3	$6.63 \times 10^{-34} \times 1.1 \times 10^{15}$ or 7.293×10^{-19} 4.6 (eV)	C1 A1	**Allow** substitution of point from graph into Einstein's equation **Allow** use of gradient as the Planck constant **Note** 4.558… eV
1.4	Any four from: • electrons may be diffracted by graphite/carbon/atoms/crystal lattice • to produce rings / circular interference fringes • diffraction of electrons occurs when the wavelength is comparable / similar to the gap size • changes in the electron's speed/energy change the size of the ring / interference fringe spacing • electrons have a (de Broglie) wavelength given by $\lambda = h/p$ • reason for the rings as opposed to linear pattern, e.g. graphite atoms are irregularly arranged.	B1x 4	
	Total	**8**	

PRACTICAL SKILLS

Complete the following practical skills-based task to improve your experimental understanding of this part of the course in preparation for **Physics Paper 3.**

Here are the measured speeds of the emerging photoelectrons from the surface of the metal.

The Planck Constant = 6.63 x 10^{-34} Js Electron Rest Mass = 9.11 x 10^{-31} kg

Wavelength, λ (nm)	Speed of Photoelectrons (x 10^5 m/s)			
300	8.55	8.56	8.53	8.56
200	12.07	12.07	12.09	12.08
150	14.77	14.82	19.22	14.78
120	17.05	17.09	17.06	17.06
100	19.10	19.07	19.07	19.08

Wavelength, λ (nm)	Frequency, f (x 10^{15} Hz)	Mean Speed, v (x 10^5 m/s)	Mean E_K (x 10^{-19} J)
300			
200			
150			
120			
100			

Analysis

A1. What were the dependent and independent variables in this investigation?

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A2. Use $c = f\lambda$ to calculate the frequency of the photons for each wavelength.

A3. Calculate the mean speed of the electrons given out for each wavelength.

A4. Use $E_K = \frac{1}{2}mv^2$ to calculate the mean kinetic energy (E_K) of the emerging photoelectrons

A5. Plot a graph of kinetic energy (on the y-axis) against the frequency (on the x-axis).

A6. Draw a line of best fit and extrapolate this to so it cuts the x-axis.

A7. Calculate the gradient of your line.

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A8. Theory states that the gradient should be equal to the Planck constant. What is the difference between you gradient and the accepted value?

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A9. What is the percentage difference of your value from the accepted value?

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A10. The threshold frequency of the metal can be obtained from your x-intercept of your graph.
What value did you obtain for the threshold frequency?

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A11. The accepted value is 0.5×10^{15} Hz, what is the difference between your value and the accepted value?

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A12. Calculate the percentage difference from the accepted value.

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A13. Using either your graph or the equation $hf = \phi + E_{K(MAX)}$ calculate the work function, ϕ

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A14. The accepted value is 2.5×10^{-19} J. What is the difference between your value and the accepted value?

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A15. What is the percentage difference of your value from the accepted value?

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A16. Calculate the uncertainty in the speed for the data from photons of wavelength 150 nm.

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A17. What is this as a percentage of the mean speed?

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TOPIC: 3.2.2.2: Collisions of Electrons with Atoms

SPEC CHECK

Specification	Completed?
Ionisation and excitation; understanding of ionisation and excitation in the fluorescent tube.	
The electron volt.	
Students will be expected to be able to convert eV into J and vice versa.	

SUBJECT KNOWLEDGE

To build your subject knowledge, answer the following questions.

WARNING: The answers are not found in this guide.

Q1. What is excitation?

Q2. What causes excitation?

Q3. What is the difference between excitation and ionisation?

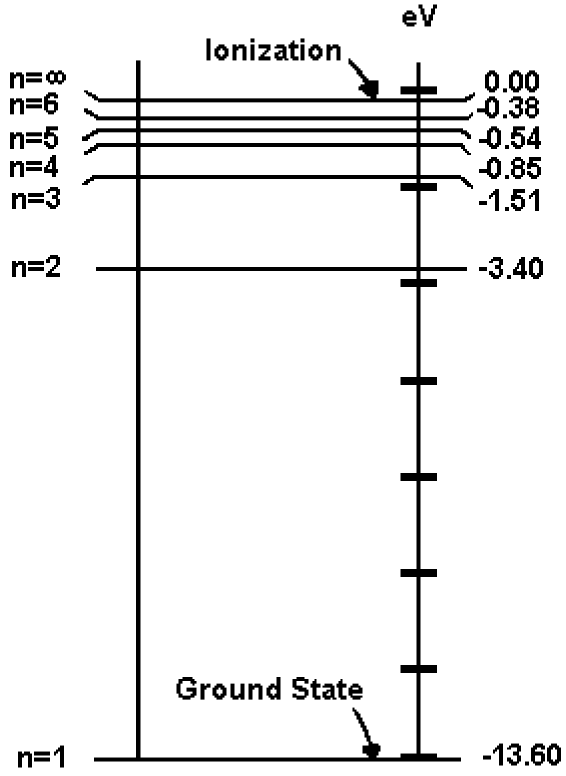
Q4. What is de-excitation?

Q5. Why are these processes considered quantum effects?

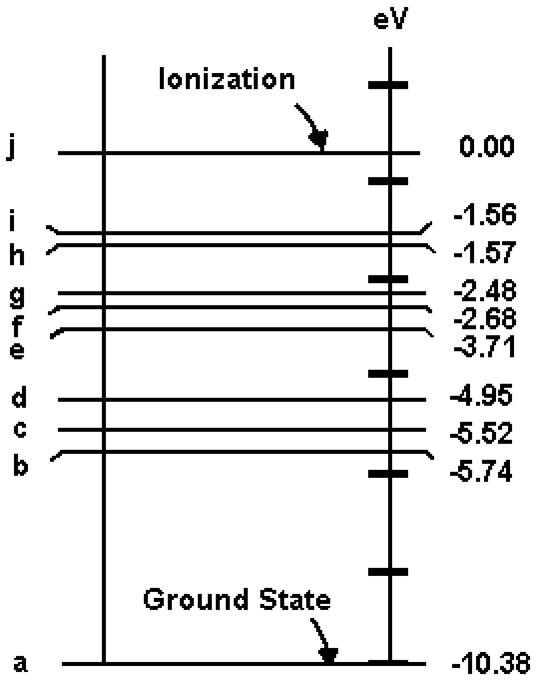
MASTERY TASK

To enhance your understanding in this topic, answer the following questions.

Energy Level Question Practice



Energy levels for the hydrogen atom



A few energy levels for the mercury atom

A1. For the following transitions, calculate the wavelength of light emitted and state which part of the electromagnetic spectrum it belongs to: -

A1.1 Hydrogen (n=2 → 1)

A1.2 Mercury (n=h → a)

A1.3 Hydrogen (n=6 → 5)

A1.4 Mercury (n=i → e)

A1.5 Hydrogen (n=4 → 2)

A2. Explain how an electron excited to the n=6 level in a hydrogen atom may emit one photon or may emit many photons.

A3. Which energy transition might a photon with the following frequencies correspond to?

A3.1 2.70×10^{14} Hz (mercury i → f)

A3.2 4.56×10^{14} Hz (hydrogen 3 → 2)

A3.3 3.15×10^{15} Hz (hydrogen 5 → 1)

TOPIC: 3.2.2.3: Energy Levels and Photo Emission

SPEC CHECK

Specification	Completed?
Line spectra (e.g. of atomic hydrogen) as evidence for transitions between discrete energy levels in atoms. $h f = E_1 - E_2$	
Observation of line spectra using a diffraction grating.	

SUBJECT KNOWLEDGE

To build your subject knowledge, answer the following questions.

WARNING: The answers are not found in this guide.

Q1. Describe line absorption.

Q2. Describe line emission spectra.

Q3. How are these spectra produced?

Q4. Explain how the coating on a fluorescent tube converts ultraviolet photons into visible photons.

PRACTICAL SKILLS

Complete the following practical skills-based task to improve your experimental understanding of this part of the course in preparation for **Physics Paper 3.**

The Paschen Series

Transition	Frequency, f ($\times 10^{14}$ Hz)			Mean f ($\times 10^{14}$ Hz)	Wavelength, λ (nm)	Energy Difference (eV)
$6 \rightarrow 3$	2.79	2.72	2.71			
$5 \rightarrow 3$	2.39	2.28	2.35			
$4 \rightarrow 3$	1.68	1.62	1.50			

The Balmer Series

Transition	Frequency, f ($\times 10^{14}$ Hz)			Mean f ($\times 10^{14}$ Hz)	Wavelength, λ (nm)	Energy Difference (eV)
$6 \rightarrow 2$	7.27	7.33	7.36			
$5 \rightarrow 2$	6.54	7.26	6.93			
$4 \rightarrow 2$	6.23	6.17	6.11			
$3 \rightarrow 2$	4.51	4.61	4.59			

The Lyman Series

Transition	Frequency, f ($\times 10^{15}$ Hz)			Mean f ($\times 10^{15}$ Hz)	Wavelength, λ (nm)	Energy Difference (eV)
$6 \rightarrow 1$	3.35	3.01	3.21			
$5 \rightarrow 1$	3.19	3.24	3.05			
$4 \rightarrow 1$	3.12	3.16	2.99			
$3 \rightarrow 1$	2.77	2.94	3.02			
$2 \rightarrow 1$	2.37	2.53	2.48			

Key Information
Infrared >750 nm, Visible Light 750 – 400 nm, Ultra Violet 10 – 400 nm Red (625–740), Orange (590–625), Yellow (565–590), Green (520–565), Cyan (500–520), Blue (435–500), Violet (380–435)

Analysis

A1. For each transition calculate the mean frequency of the photon emitted.

A2. Use the wave speed equation, $c = f\lambda$ to calculate the wavelength of the photon.

A3. Using $E = hf$ calculate the energy of the photon in Joules. Convert this to electronvolts and record it in the table.

A4. What is the uncertainty in the frequency of the 4 → 3 transition?

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A5. Calculate this as a percentage of the mean frequency for this transition.

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A6. What is the uncertainty in the frequency of the 5 → 2 transition?

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A7. Calculate this as a percentage of the smallest frequency for this transition.

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A8. What is the uncertainty in the frequency of the 6 → 1 transition?

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A9. Calculate this as a percentage of the largest frequency for this transition.

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A10. For each transition state what type of photon from the EM Spectrum is emitted.

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A11. For photons in the Visible Light region of the EM Spectrum state which colour the photon would be.

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A12. If the ground state (n=1) has an energy of – 13.6 eV draw an energy level diagram for Hydrogen including values for each energy level.

EXTENDED WRITING

To enhance your skills in answering examination questions for the A-Level examinations, complete the following task.

Line spectra were observed before they could be explained by theory. We now know that photons of characteristic frequency are emitted from the vapour of an element. The spectrum of the light emitted contains lines, each of a definite wavelength. Explain how this supports the idea that atoms have discrete energy levels.
Your explanation should include:

- What in meant by the 'ground state' of an atom
- What the process of excitation involves and how it occurs
- How line spectra are produced
- How this leads to the idea of discrete energy levels
- How a florescent tube works with an explanation of the purpose of the white coating.

ANSWERING SPACE

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ASSESSMENT FEEDBACK

P	**Praise. What were the positive aspects of the work? What did they do well? What skills did they demonstrate?**

I	**Improvements. What were the literacy issues in the piece of work?**		*Write in ink.*		*Draw in Pencil.*		*Use a ruler.*
	Always use capital letters at the beginning of a sentence.		Learn the spellings identified in your work.				
	Always use capital letters for proper nouns.		Ensure sentences make sense.				
	Make sure you write on the line and not above or below it.		Use correct punctuation.				
	Use scientific vocabulary appropriate to the task.		Vary your sentences to demonstrate your understanding.				

D answer		**B answer**		**A* answer**	
The ground state is the lowest **or** most stable energy level.		The ground state is the lowest and most stable energy level...		...that an atom/electron can occupy (owtte).	
Excitation involves an (orbital) electron moving to a higher energy level...		...when it is given the <u>exact</u> amount of energy by absorbing a photon...		...or a collision with another (current/fast moving) electron.	
When electrons deexcite (move to a lower energy level) they release a photon...		...that has energy equal to the energy difference of the energy levels that it has moved between... *This could have been shown using the equations.*		...the electron could fall straight to the ground state or fall to the various levels between its excited energy level and the ground state.	
Photons released will have a particular* energy which means a specific colour is produced...		...each ΔE is linked to the frequency of the photon and hence the wavelength (which governs colour)...		...so a range of coloured photons are released. * discrete is used instead of particular	
If the photons have a fixed energy then the energy levels must have a fixed value.		Each element produces a range of photons with fixed values of wavelength (and frequency)...		...suggesting fixed values of the energy levels.	
In a florescent tube a current is passed through a tube of ~ gas†. The electrons (current) collide with the (orbital) electrons of the gas†...		...which excites them to a higher energy level. The electron then falls down to a more stable/lower energy level and releases a photon...		~ mercury † vapour is used instead of gas	
The white coating is for protection. It changes the frequency/wavelength of the light.		The powder absorbs the high energy # photons emitted by the vapour ¤ and gives out visible light...		# ultra violet (UV) ¤ which are dangerous to humans	

N	**Next Steps. How can they move their work onto the next grade? What didn't they include?**	**Grade**	**Effort**

CHALLENGE QUESTION

To assess your understanding, answer the following higher-level question on this topic.

1. Fig. 21.1 shows some of the energy levels of electrons in hydrogen gas atoms. The energy levels are labelled **A, B, C** and **D.**

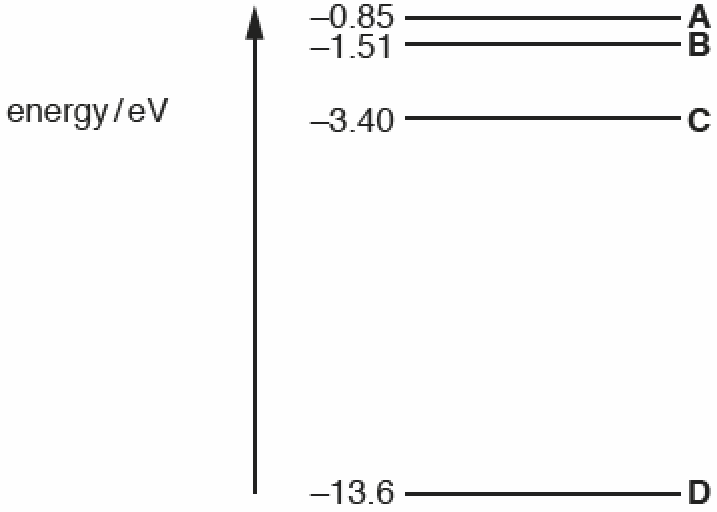

Fig. 21.1 (not to scale)

1.1 Explain why the energy levels are negative.

[1 Mark]

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1.2 An electron makes a transition (jump) from level **C** to level **A**.
Calculate the energy gained by this electron.

[1 Mark]

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Energy = ... eV

Calculate the wavelength in nm of the photon absorbed by this electron.

[3 Marks]

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Wavelength = ... nm

Light from a distant galaxy is passed through a diffraction grating. **Fig. 21.2** shows the part of the spectrum of light that shows a strong hydrogen-alpha emission line.

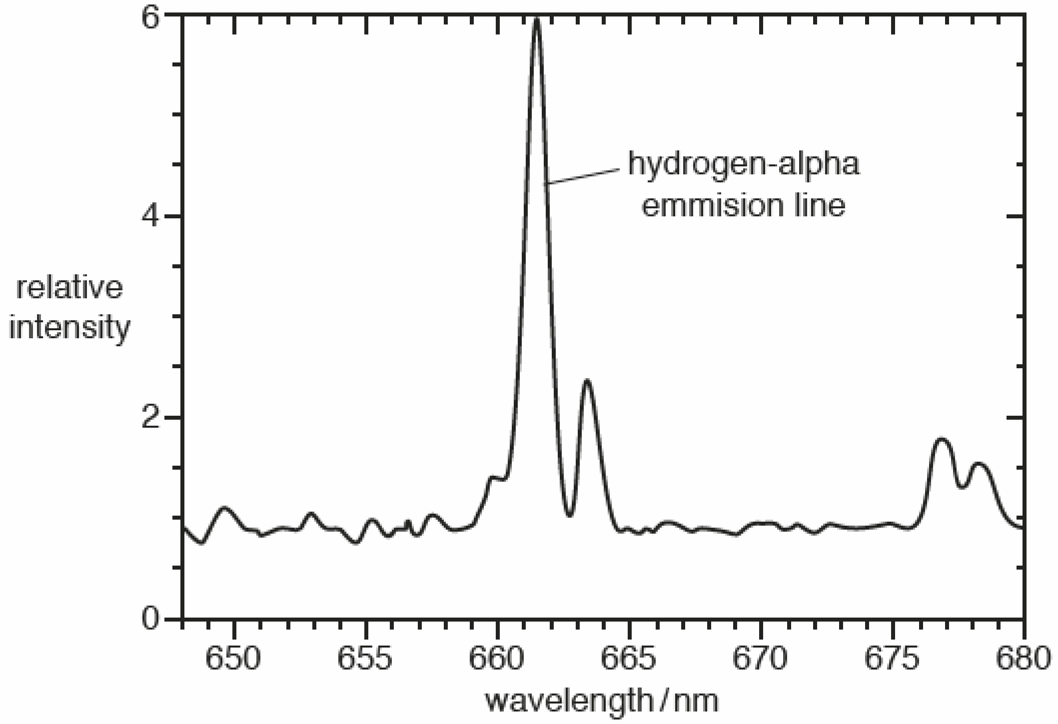

Fig. 21.2

1.3 State how an emission line is produced.

[1 Mark]

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1.4 State an adjustment that could be made to the experimental arrangement that would space the emission lines more widely.

[1 Mark]

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MARK SCHEME

Question	Answer	Marks	Guidance
1.1	electron bound to nucleus / represents energy electron must gain to leave the atom / total energy of electron in atom is less than that of a free electron	B1	**Allow** ionisation level defined as zero as AW for 'represents electron must gain energy to leave atom / move up energy level' **Allow** potentials for attractive forces are negative.
1.2	energy = 2.55 (eV)	B1	Ignore sign
	energy = 2.55 × 1.60 × 10^{-19} (J)	C1	Possible ECF from **(ii)1**
	$\lambda = \frac{6.63\times10^{-34}\times3.0\times10^{8}}{2.55\times1.60\times10^{-19}}$ (Allow any subject)	C1	
	wavelength = 4.9 × 10^{-7} (m) wavelength = 490 (nm)	A1	**Note:** wavelength = 488 (nm) to 3 sf
1.3	Electron(s) makes a transition to a lower (energy) level / loses energy **and** emitting a photon(s) / EM radiation	B1	
1.4	Reduce grating separation / increase distance between grating and screen	B1	**Allow** 'use finer grating' or 'use grating with more lines mm^{-1}' **Not** 'smaller slit size'

TOPIC: 3.2.2.4: Wave-Particle Duality
SPEC CHECK

Specification	Completed?
Students should know that electron diffraction suggests that particles possess wave properties and the photoelectric effect suggests that electromagnetic waves have a particulate nature.	
de Broglie wavelength $\lambda = h/mv$ where mv is the momentum.	
Students should be able to explain how and why the amount of diffraction changes when the momentum of the particle is changed.	
Appreciation of how knowledge and understanding of the nature of matter changes over time.	
Appreciation that such changes need to be evaluated through peer review and validated by the scientific community.	
Demonstration using an electron diffraction tube.	

SUBJECT KNOWLEDGE

To build your subject knowledge, answer the following questions.

WARNING: The answers are not found in this guide.

Q1. What observations show light to have a 'wave-like' character?

Q2. What observations show light to have a 'particle-like' character?

Q3. What happens to the de Broglie wavelength of a particle if its momentum increases? How does this affect the particle diffraction pattern?

Q4. Particle A has a de Broglie wavelength of 8×10^{-10}m and particle B has a de Broglie wavelength of 2×10^{-19}m. If the particles are travelling at the same speed, which particle has the greater mass?

Q5. Which observations show electrons to have a 'wave-like' character?

MASTERY TASK

To enhance your understanding in this topic, answer the following questions.

$h = 6.63 \times 10^{-34}$ J s

A1. Determine the de Broglie wavelength of the matter wave associated with a cricket ball of mass 0.175 kg and velocity 23.6 m s^{-1}. Use the answer to this question to explain why we do not observe the matter waves associated with macroscopic objects.

A2. Calculate the de Broglie wavelength of an electron travelling at 10^6 m/s. (Mass of electron is 9.11×10^{-31} kg.) Use the answer to this question to explain why we would expect to observe the effects of the matter waves associated with electrons. Give one example of these effects.

A3. A proton is travelling at a speed of 1.5×10^7 m s^{-1}. Determine the de Broglie wavelength of the proton, given its mass is 1.67×10^{-27} kg.

A4. Calculate the momentum of a neutron if it has a de Broglie wavelength of 1.59×10^{-13} m.

A5. Determine the speed of the neutron in Q4, given that the mass of a neutron is 1.67×10^{-27} kg.

A6. An electron volt (eV) is an energy unit equivalent to the work done when an electron is accelerated through a potential difference of 1 volt. If an electron has a kinetic energy of 100 eV, what is its associated de Broglie wavelength? (Charge on an electron is 1.6×10^{-19} C).

Working Out Space

Answers

A1. $\lambda = 1.61 \times 10^{-34}$ m
A2. $\lambda = 7.28 \times 10^{-10}$ m
A3. $\lambda = 2.65 \times 10^{-14}$ m
A4. $p = 4.17 \times 10^{-21}$ kg m s^{-1}
A5. $v = 2.50 \times 10^{6}$ m s^{-1}
A6. $\lambda = 1.23 \times 10^{-10}$ m

PRACTICAL SKILLS

Complete the following practical skills-based task to improve your experimental understanding of this part of the course in preparation for **Physics Paper 3.**

Experimental Data

Here are the measured wavelengths of the electrons travelling at certain velocities.
Electron rest mass = 9.11×10^{-31} kg

Velocity, *v* (m/s)	**De Broglie Wavelength, *λ* (x 10^{-4} m)**			**Mean *λ* (x 10^{-4} m)**	***1 / λ* (m^{-1})**
5	14.63	14.54	14.51		
6	12.01	12.18	12.20		
7	10.39	10.38	10.43		
8	9.09	9.05	9.16		
9	8.29	8.01	7.97		
10	7.31	7.14	7.39		

Analysis

A1. What is the independent variable in this investigation?

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A2. What is the dependent variable in this investigation?

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A3. What is the resolution of the wavelength measurements?

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A4. What is the resolution of the velocity measurements?

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A5. What is the uncertainty in the velocity measurements?

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A6. Calculate the percentage uncertainty in the velocity measurement of 8 m/s

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A7. Calculate the mean values of the de Broglie wavelength for each velocity.

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A8. For each mean value calculate 1 / λ.

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A9. Calculate the uncertainty in the measurement of λ when v is 5 m/s.

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A10. What is this as a percentage of the mean value?

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A11. Calculate the uncertainty in the measurement of λ when v is 7 m/s.

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A12. What is this as a percentage of the mean value?

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A13. Calculate the uncertainty in the measurement of λ when v is 9 m/s.

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A14. What is this as a percentage of the mean value?

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A14. Plot a graph of *v* against 1 / *λ* and draw a line of best fit.

A15. Does the line pass through the origin? Should it? Explain your answer.

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A16. Calculate the gradient of your line of best fit.

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A17. If v and 1 / λ are linked by the equation $\lambda = \frac{h}{mv}$, what does the gradient of your line of best fit represent?

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A18. Use your gradient to calculate a value of Planck's constant, *h*.

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A19. The accepted value is 6.63×10^{-34}, what is the different between your value and the accepted value?

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A20. What is this as a percentage of the accepted value?

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CHALLENGE QUESTION

To assess your understanding, answer the following higher-level question on this topic.

1.1 State one piece of evidence for the wave-like behaviour of electrons.

[1 Mark]

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In an electron-gun, each electron is accelerated to a maximum kinetic energy of 210 eV.

1.2 Show that the final speed of each electron is about 9×10^6 m s^{-1}.

[3 Marks]

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1.3 Calculate the de Broglie wavelength λ of each electron.

[2 Marks]

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λ = ... m

1.4 Electromagnetic waves interact with matter as photons.
Explain the photoelectric effect using ideas of **photons, conservation of energy** and **work function.**

[4 Marks]

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MARK SCHEME

Question	Answer	Marks	Guidance
1.1	Diffraction (of electrons by matter)	**B1**	
1.2	(*KE* =) 210 × 1.60 × 10^{-19} (J) **or** 3.36 × 10^{-17} (J)	**C1**	**Note** using *KE* = 210 (J) is wrong physics XP
	½ × 9.11 × 10^{-31} × v^2 = 3.36 × 10^{-17}	**C1**	
	v = 8.6 × 10^6 (m s^{-1})	**A1**	**Note** the answer must be to more than 1 SF
1.3	$\lambda = \frac{6.63\times10^{-34}}{9.11\times10^{-31}\times 8.6\times10^{6}}$	**C1**	Possible ECF from **(i)**
	λ = 8.5 × 10^{-11} (m)	**A1**	**Allow** 2 marks for 8.1 × 10^{-11} (m); v = 9 × 10^6 m s^{-1} used
1.4			**Ignore** references to frequencies and threshold frequency **Allow photo**electron instead of electron throughout
	One photon interacts with one electron	**B1**	
	energy of photon = (maximum) *KE* (of electron) + work function (of the metal)	**B1**	**Note** an equation is required **Allow** $hf = KE_{(max)} + \phi$, with *hf = energy of photon, $KE_{(max)}$ = (maximum) *KE* (of electron) and ϕ = work function ***Not** hf = Planck constant × frequency (since there is no reference to 'energy of photon') **Allow** energy of photon**s** = ……… as BOD
	Work function is the **minimum energy** (required) to remove **electron** (from the surface of a metal)	**B1**	**Allow** ϕ instead of work function for this mark **Allow** 'work done' instead of 'energy' **Allow** … electron**s** …. as BOD
	Electron removed / photoelectric effect when energy of photon is greater than / equal to work function (of the metal)	**B1**	**Allow** electron removed / photoelectric effect when $hf > \phi$ or electron removed / photoelectric effect when $hf = \phi$ or electron not removed / no photoelectric effect when $hf < \phi$ **Allow** electron**s** and photon**s** as BOD
	Total	**10**	

EXTENSION

Structure of the photomultiplier tube

A photomultiplier tube consists of a vacuum chamber with a photocathode at one end and an anode at the other. Between these two electrodes lie a focussing electrode and a series of small curved electrodes known as **dynodes**. The dynodes are set at increasing positive potentials with a potential difference (pd) of around 100 V between each. The pds cause electrons to be accelerated from the direction of the photocathode towards the anode.

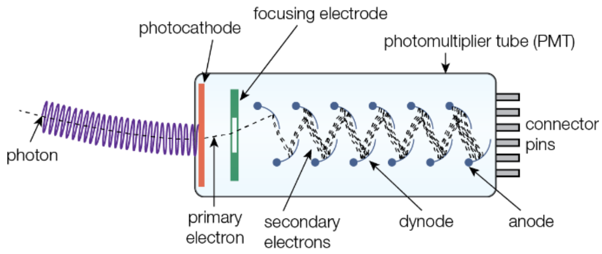

Figure 1

How the photomultiplier tube works

A photon strikes the photocathode producing a single electron through the photoelectric effect. This first electron is referred to as the primary electron.

The primary electron passes through a focussing electrode which directs it towards the first dynode.

The first dynode is at a higher positive pd than the photocathode, and so the primary electron is accelerated towards it.

The primary electron strikes the dynode and causes the emission of several electrons through a process called secondary emission. (The primary electron is absorbed by the material and provides energy to release a burst of several secondary electrons.)

The secondary electrons are accelerated towards the second dynode where each of the electrons strikes the surface, are absorbed, and causes further emissions of secondary electrons which accelerate towards the next dynode.

After several stages, the initial single electron has been 'multiplied' hundreds of thousands of times to give a surge of electrons which reach the cathode.

The time taken between the primary electron being produced and the secondary electron pulse reaching the anode is easy to calculate, and so the exact time that the photon was produced can be measured precisely.

Questions

All of the questions are about the same photomultiplier tube.

1.1 If the photocathode is constructed from a material with a work function of 4.00 eV, calculate the minimum frequency of a photon which can trigger the photomultiplier.

[2 Marks]

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2. The potential difference between the photocathode and the first dynode is 100 V.
The potential difference between each of the subsequent dynodes is also 100 V.

2.1 State the energy gained by an electron travelling between one dynode and the next.

[1 Mark]

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2.2 If each secondary electron requires 3.20×10^{-18} J to be released through secondary emission, calculate how many secondary electrons are released by the primary electron at the first dynode.

[2 Marks]

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2.3 A photomultiplier tube has 11 dynodes and an anode as shown in **Figure 1.**
If the maximum number of electrons are released at each stage, calculate the total charge which will reach the anode for each primary electron produced by the photocathode.

[3 Marks]

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3. Assuming that the secondary electrons are ejected with zero kinetic energy and that secondary emission is instantaneous, calculate:

3.1 The velocity of the secondary electrons as they reach the next dynode in the sequence

[2 Marks]

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3.2 The minimum time taken for the electrons to travel between one dynode and the next, if the dynodes are separated by 5.00 mm

[2 Marks]

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3.3 The time between the initial interaction at the photocathode and the electron pulse at the anode, assuming that the separation of the photocathode and first dynode is 5.00 mm as is the separation of the final dynode and anode.

[2 Marks]

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3.4 Discuss the effect on the size of the current pulse if a photon of frequency 2.00×10^{15} Hz interacts with the photocathode. State any assumptions that you make and support your argument with calculations where appropriate.

[4 Marks]

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ANSWERS

1 $E = 4.00 \times 1.60 \times 10^{-19}$ (*1 mark*)

$f = \frac{E}{h} = 9.65 \times 10^{14}$ Hz (*1 mark*)

2.1 100 eV (*1 mark*)

2.2 100 eV = 1.60×10^{-17} J (*1 mark*)

Electrons = $1.60 \times 10^{-17} / 3.2 \times 10^{-18}$ = 5 electrons (*1 mark*)

2.3 Noting there are 11 stages which produce secondary electrons (*1 mark*)

electrons = $5^{11} = 4.88 \times 10^{7}$ electrons (*1 mark*)

charge = $4.88 \times 10^{7} \times 1.60 \times 10^{-19} = 7.81 \times 10^{-12}$ C (*1 mark*)

3.1 $v = \sqrt{2\frac{E}{m}}$ (*1 mark*)

$= 5.93 \times 10^{6}$ m s^{-1} (*1 mark*)

3.2 $s = \frac{(u+v)t}{2}$ to give $t = \frac{2s}{u+v}$ (*1 mark*)

$t = 1.69 \times 10^{-9}$ s (*1 mark*)

3.3 Note that there are 12 'stages' (*1 mark*)

$t = 12 \times 1.69 \times 10^{-9} = 2.02 \times 10^{-8}$ s (*1 mark*)

3.4 Calculation of kinetic energy provided to photoelectron (4.29 eV) (*1 mark*),

assume that the emitted electrons would be travelling directly towards the first dynode (*1 mark*),

note that this additional energy is not sufficient to release any additional secondary electrons (they require 20 eV each) (*1 mark*),

and so current pulse is the same size (*1 mark*).

REVISION CHECKLIST

Specification reference	Checklist questions	
3.2.2.1	Can you explain threshold frequency and the photon explanation of threshold frequency?	☐
3.2.2.1	Can you explain work function ϕ and stopping potential?	☐
3.2.2.1	Can you recognise and use the photoelectric equation: $hf = \phi + E_{K\,(max)}$?	☐
3.2.2.1	Can you explain that $E_{K\,(max)}$ is the maximum kinetic energy of the photoelectrons?	☐
3.2.2.2	Can you explain ionisation and excitation?	☐
3.2.2.2	Can you describe the electron volt?	☐
3.2.2.2	Can you convert eV into J and vice versa?	☐
3.2.2.3	Can you use line spectra as evidence for transitions between discrete energy levels in atoms?	☐
3.2.2.3	Can you use the formula $hf = E_1 - E_2$?	☐
3.2.2.4	Can you explain why electron diffraction suggests that particles possess wave properties and the photoelectric effect suggests that electromagnetic waves have a particulate nature?	☐
3.2.2.4	Can you calculate the de Broglie wavelength using $\lambda = \frac{h}{mv}$, where mv is the momentum?	☐
3.2.2.4	Can you explain how and why the amount of diffraction changes when the momentum of the particle is changed?	☐
3.2.2.4	Can you explain that knowledge and understanding of the nature of matter changes over time?	☐
3.2.2.4	Can you explain that changes in understanding of the nature of matter need to be evaluated through peer review and validated by the scientific community?	☐

DATASHEET

DATA – FUNDAMENTAL CONSTANTS AND VALUES

Quantity	Symbol	Value	Units
speed of light in vacuo	c	3.00×10^{8}	$\mathrm{m\,s^{-1}}$
permeability of free space	μ_0	$4\pi \times 10^{-7}$	$\mathrm{H\,m^{-1}}$
permittivity of free space	ε_0	8.85×10^{-12}	$\mathrm{F\,m^{-1}}$
magnitude of the charge of electron	e	1.60×10^{-19}	C
the Planck constant	h	6.63×10^{-34}	J s
gravitational constant	G	6.67×10^{-11}	$\mathrm{N\,m^{2}\,kg^{-2}}$
the Avogadro constant	N_A	6.02×10^{23}	$\mathrm{mol^{-1}}$
molar gas constant	R	8.31	$\mathrm{J\,K^{-1}\,mol^{-1}}$
the Boltzmann constant	k	1.38×10^{-23}	$\mathrm{J\,K^{-1}}$
the Stefan constant	σ	5.67×10^{-8}	$\mathrm{W\,m^{-2}\,K^{-4}}$
the Wien constant	α	2.90×10^{-3}	m K
electron rest mass (equivalent to 5.5×10^{-4} u)	m_e	9.11×10^{-31}	kg
electron charge/mass ratio	$\frac{e}{m_e}$	1.76×10^{11}	$\mathrm{C\,kg^{-1}}$
proton rest mass (equivalent to 1.00728 u)	m_p	$1.67(3) \times 10^{-27}$	kg
proton charge/mass ratio	$\frac{e}{m_p}$	9.58×10^{7}	$\mathrm{C\,kg^{-1}}$
neutron rest mass (equivalent to 1.00867 u)	m_n	$1.67(5) \times 10^{-27}$	kg
gravitational field strength	g	9.81	$\mathrm{N\,kg^{-1}}$
acceleration due to gravity	g	9.81	$\mathrm{m\,s^{-2}}$
atomic mass unit (1u is equivalent to 931.5 MeV)	u	1.661×10^{-27}	kg

ALGEBRAIC EQUATION

quadratic equation $x = \dfrac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

ASTRONOMICAL DATA

Body	Mass/kg	Mean radius/m
Sun	1.99×10^{30}	6.96×10^{8}
Earth	5.97×10^{24}	6.37×10^{6}

GEOMETRICAL EQUATIONS

arc length	$= r\theta$
circumference of circle	$= 2\pi r$
area of circle	$= \pi r^2$
curved surface area of cylinder	$= 2\pi rh$
area of sphere	$= 4\pi r^2$
volume of sphere	$= \frac{4}{3}\pi r^3$

Particle Physics

Class	Name	Symbol	Rest energy/MeV
photon	photon	γ	0
lepton	neutrino	ν_e	0
		ν_μ	0
	electron	$e^\pm$	0.510999
	muon	$\mu^\pm$	105.659
mesons	π meson	$\pi^\pm$	139.576
		π^0	134.972
	K meson	$K^\pm$	493.821
		K^0	497.762
baryons	proton	p	938.257
	neutron	n	939.551

Properties of quarks

antiquarks have opposite signs

Type	Charge	Baryon number	Strangeness
u	$+\frac{2}{3}e$	$+\frac{1}{3}$	0
d	$-\frac{1}{3}e$	$+\frac{1}{3}$	0
s	$-\frac{1}{3}e$	$+\frac{1}{3}$	-1

Properties of Leptons

		Lepton number
Particles:	$e^-, \nu_e; \mu^-, \nu_\mu$	$+1$
Antiparticles:	$e^+, \overline{\nu_e}, \mu^+, \overline{\nu_\mu}$	-1

Photons and energy levels

photon energy $E = hf = hc/\lambda$

photoelectricity $hf = \phi + E_{k\,(max)}$

energy levels $hf = E_1 - E_2$

de Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{mv}$

Waves

wave speed $c = f\lambda$ *period* $f = \frac{1}{T}$

first harmonic $f = \frac{1}{2l}\sqrt{\frac{T}{\mu}}$

fringe spacing $w = \frac{\lambda D}{s}$ *diffraction grating* $d \sin\theta = n\lambda$

refractive index of a substance s, $n = \frac{c}{c_s}$

for two different substances of refractive indices n_1 *and* n_2,

law of refraction $n_1 \sin\theta_1 = n_2 \sin\theta_2$

critical angle $\sin\theta_c = \frac{n_2}{n_1}$ for $n_1 > n_2$

Mechanics

moments moment $= Fd$

velocity and acceleration $v = \frac{\Delta s}{\Delta t}$ $a = \frac{\Delta v}{\Delta t}$

equations of motion $v = u + at$ $s = \left(\frac{u+v}{2}\right)t$

$v^2 = u^2 + 2as$ $s = ut + \frac{at^2}{2}$

force $F = ma$

force $F = \frac{\Delta(mv)}{\Delta t}$

impulse $F\Delta t = \Delta(mv)$

work, energy and power $W = Fs\cos\theta$

$E_k = \frac{1}{2}mv^2$ $\Delta E_p = mg\Delta h$

$P = \frac{\Delta W}{\Delta t}$, $P = Fv$

$efficiency = \frac{useful\ output\ power}{input\ power}$

Materials

density $\rho = \frac{m}{V}$ *Hooke's law* $F = k\Delta L$

Young modulus $= \frac{\text{tensile stress}}{\text{tensile strain}}$ *tensile stress* $= \frac{F}{A}$ *tensile strain* $= \frac{\Delta L}{L}$

energy stored $E = \frac{1}{2}F\Delta L$

Electricity

current and pd $I = \frac{\Delta Q}{\Delta t}$ $V = \frac{W}{Q}$ $R = \frac{V}{I}$

resistivity $\rho = \frac{RA}{L}$

resistors in series $R_T = R_1 + R_2 + R_3 + \ldots$

resistors in parallel $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$

power $P = VI = I^2R = \frac{V^2}{R}$

emf $\varepsilon = \frac{E}{Q}$ $\varepsilon = I(R + r)$

Circular motion

magnitude of angular speed $\omega = \frac{v}{r}$

$\omega = 2\pi f$

centripetal acceleration $a = \frac{v^2}{r} = \omega^2 r$

centripetal force $F = \frac{mv^2}{r} = m\omega^2 r$

Simple harmonic motion

acceleration $a = -\omega^2 x$

displacement $x = A \cos(\omega t)$

speed $v = \pm\omega\sqrt{(A^2 - x^2)}$

maximum speed $v_{max} = \omega A$

maximum acceleration $a_{max} = \omega^2 A$

for a mass-spring system $T = 2\pi\sqrt{\frac{m}{k}}$

for a simple pendulum $T = 2\pi\sqrt{\frac{l}{g}}$

Thermal physics

energy to change temperature $Q = mc\Delta\theta$

energy to change state $Q = m\,l$

gas law $pV = nRT$

$pV = NkT$

kinetic theory model $pV = \frac{1}{3}N\,m\,(c_{rms})^2$

kinetic energy of gas molecule $\frac{1}{2}m\,(c_{rms})^2 = \frac{3}{2}kT = \frac{3RT}{2N_A}$

Gravitational fields

force between two masses $F = \frac{Gm_1m_2}{r^2}$

gravitational field strength $g = \frac{F}{m}$

magnitude of gravitational field strength in a radial field $g = \frac{GM}{r^2}$

work done $\Delta W = m\Delta V$

gravitational potential $V = -\frac{GM}{r}$

$g = -\frac{\Delta V}{\Delta r}$

Electric fields and capacitors

force between two point charges $F = \frac{1}{4\pi\varepsilon_0}\frac{Q_1Q_2}{r^2}$

force on a charge $F = EQ$

field strength for a uniform field $E = \frac{V}{d}$

work done $\Delta W = Q\Delta V$

field strength for a radial field $E = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r^2}$

electric potential $V = \frac{1}{4\pi\varepsilon_0}\frac{Q}{r}$

$E = \frac{\Delta V}{\Delta r}$

capacitance $C = \frac{Q}{V}$

$C = \frac{A\varepsilon_0\varepsilon_r}{d}$

capacitor energy stored $E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$

capacitor charging $Q = Q_0(1 - e^{-t/RC})$

decay of charge $Q = Q_0e^{-t/RC}$

time constant RC

Magnetic fields

force on a current	$F = BIl$
force on a moving charge	$F = BQv$
magnetic flux	$\Phi = BA$
magnetic flux linkage	$N\Phi = BAN\cos\theta$
magnitude of induced emf	$\varepsilon = N\frac{\Delta\Phi}{\Delta t}$
	$N\Phi = BAN\cos\theta$
emf induced in a rotating coil	$\varepsilon = BAN\omega\sin\omega t$
alternating current	$I_{rms} = \frac{I_0}{\sqrt{2}}$ $\quad V_{rms} = \frac{V_0}{\sqrt{2}}$
transformer equations	$\frac{N_s}{N_p} = \frac{V_s}{V_p}$
	$efficiency = \frac{I_s V_s}{I_p V_p}$

Nuclear physics

the inverse square law for γ radiation	$I = \frac{k}{x^2}$
radioactive decay	$\frac{\Delta N}{\Delta t} = -\lambda N,\ N = N_0 e^{-\lambda t}$
activity	$A = \lambda N$
half-life	$T_{½} = \frac{\ln 2}{\lambda}$
nuclear radius	$R = R_0 A^{1/3}$
energy-mass equation	$E = mc^2$

OPTIONS

Astrophysics

1 astronomical unit = 1.50×10^{11} m

1 light year = 9.46×10^{15} m

1 parsec = 206265 AU = 3.08×10^{16} m = 3.26 light year

Hubble constant, H = 65 km s^{-1} Mpc^{-1}

$$M = \frac{\text{angle subtended by image at eye}}{\text{angle subtended by object at unaided eye}}$$

in normal adjustment	$M = \frac{f_0}{f_e}$
Rayleigh criterion	$\theta \approx \frac{\lambda}{D}$
magnitude equation	$m - M = 5\log\frac{d}{10}$
Wien's law	$\lambda_{max} T = 2.9 \times 10^{-3}$ m K
Stefan's law	$P = \sigma A T^4$
Schwarzschild radius	$R_s \approx \frac{2GM}{c^2}$
Doppler shift for v << c	$\frac{\Delta f}{f} = -\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$
red shift	$z = -\frac{v}{c}$
Hubble's law	$v = Hd$

Medical physics

lens equations	$P = \frac{1}{f}$
	$m = \frac{v}{u}$
	$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$
threshold of hearing	$I_0 = 1.0 \times 10^{-12}$ W m^{-2}
intensity level	$intensity\ level = 10\log\frac{I}{I_0}$
absorption	$I = I_0 e^{-\mu x}$
	$\mu_m = \frac{\mu}{\rho}$
ultrasound imaging	$Z = \rho c$
	$\frac{I_r}{I_i} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$
half-lives	$\frac{1}{T_E} = \frac{1}{T_B} + \frac{1}{T_P}$

Engineering physics

moment of inertia $I = \Sigma mr^2$

angular kinetic energy $E_k = \frac{1}{2} I\omega^2$

equations of angular motion $\omega_2 = \omega_1 + \alpha t$

$\omega_2{}^2 = \omega_1{}^2 + 2\alpha\theta$

$\theta = \omega_1 t + \frac{\alpha t^2}{2}$

$\theta = \frac{(\omega_1 + \omega_2)\, t}{2}$

torque $T = I\,\alpha$

$T = F\,r$

angular momentum $\text{angular momentum} = I\omega$

angular impulse $T\Delta t = \Delta(I\omega)$

work done $W = T\theta$

power $P = T\omega$

thermodynamics $Q = \Delta U + W$

$W = p\Delta V$

adiabatic change $pV^\gamma = \text{constant}$

isothermal change $pV = \text{constant}$

heat engines

efficiency $= \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H}$

maximum theoretical efficiency $= \frac{T_H - T_C}{T_H}$

work done per cycle = area of loop

input power = calorific value × fuel flow rate

indicated power = $(\text{area of } p - V \text{ loop}) \times (\text{number of cycles per second}) \times (\text{number of cylinders})$

output or brake power $P = T\omega$

friction power = indicated power – brake power

heat pumps and refrigerators

refrigerator: $COP_{ref} = \frac{Q_C}{W} = \frac{Q_C}{Q_H - Q_C}$

heat pump: $COP_{hp} = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C}$

Turning points in physics

electrons in fields $F = \frac{eV}{d}$

$F = Bev$

$r = \frac{mv}{Be}$

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

Millikan's experiment $\frac{QV}{d} = mg$

$F = 6\pi\eta rv$

Maxwell's formula $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$

$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}}$

special relativity $t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$

$l = l_0 \sqrt{1 - \frac{v^2}{c^2}}$

$E = mc^2 = \frac{m_0 c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$

Electronics

resonant frequency $f_0 = \frac{1}{2\pi\sqrt{LC}}$

Q-factor $Q = \frac{f_0}{f_B}$

operational amplifiers: open loop $V_{out} = A_{OL}(V_+ - V_-)$

inverting amplifier $\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$

non-inverting amplifier $\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$

summing amplifier $V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \cdots\right)$

difference amplifier $V_{out} = (V_+ - V_-)\frac{R_f}{R_1}$

Bandwidth requirement:

for AM $\text{bandwidth} = 2f_M$

for FM $\text{bandwidth} = 2(\Delta f + f_M)$

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All relevant information has been credited in the document.

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This document has been produced for the AQA A Level Physics Specification.

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Only constructive and reasoned feedback will be considered.