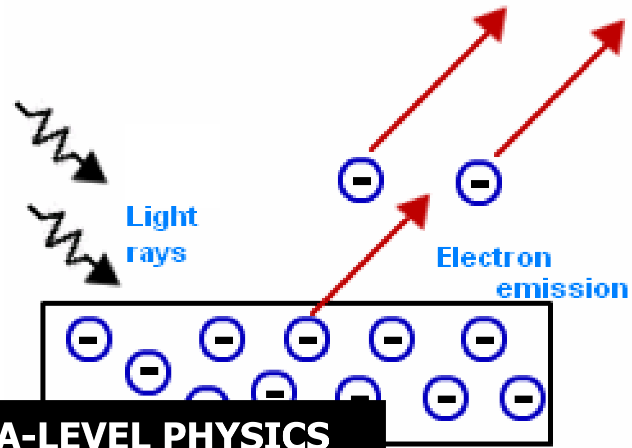
ST MARY'S SCIENCE DEPARTMENT:
PHYSICS

Volume
One

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

NAME	
PHYSICS CLASS	
MODULE TEACHER	
ALPS GRADE	



A-LEVEL PHYSICS
TOPIC 2
CLASS 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, along with the preparatory reading notes and independent work, must be brought to all Physics lessons with the appropriate teacher.

This book may be used as a learning resource in lessons, you are not fully equipped to learn if this is not used in lesson.

This book may also be used as a revision resource for intervention, internal assessments and external assessments.
Please keep this in your student file.

There are several activities in this book which may not be covered in lessons.

It is advised that students complete these activities outside of lessons as revision aides.

Definition List

Definitions you must learn for this module.

Key Word	Symbol	Definition
Photoelectric Effect		The emission of electrons from the surface of a metal by electromagnetic radiation.
Photoelectron		An electron which has been emitted when light falls on the surface of a metal.
Work Function	**ϕ**	The minimum amount of the work necessary to remove a free electron from the surface of the material.
Threshold Frequency	**f_o**	The minimum frequency of an incident radiation required to just remove an electron from the surface of a metal.
Stopping Potential	**V_s**	The potential difference necessary to stop any electron from moving (i.e. convert its kinetic energy into potential energy).
Wave–Particle Duality		Every particle may be partly described in terms not only of particles, but also of waves. It expresses the inability of the classical concepts "particle" or "wave" to fully describe the behaviour of quantum-scale objects.
Energy Level		An orbit followed by electrons around an atom's nucleus.
Excitation		When an electron gains the exact amount of energy to move up one or more energy levels.
De-excitation		When an electron gives out the exact amount of energy to move back down to its original energy level.
Ionisation		When an electron can gain enough energy to be completely removed from the atom.
Ionisation Energy		The amount of energy needed to remove an electron from the ground state.
Ground State		The lowest possible energy level in an atom (which is not the nucleus).
Line Spectrum		A series of bright (or dark lines) against a background – each line corresponds to a particular wavelength of light emitted by the source.
De Broglie Wavelength		The wavelength of particulate matter – which is used to represent the wave-like behaviour of particles.

IMPORTANT NOTE
These definitions must be memorised by students.

You will be tested on these definitions.

Equations

The equations below are used in this module.

Quantity/Concept	**Equation(s)**
Photoelectric Effect Equation	$E = hf = \phi + ½ mv^2{}_{max}$
Threshold Frequency	$f_o = \phi/h$ Equation not given in the examination
Stopping Potential	$V_s = E_{k\ max} / e$ Synoptic Link with Electric Fields
Excitation and De-Excitation	$\Delta E = hf = hc / \lambda = E_1 - E_2$
de Broglie Wavelength	$\lambda = h/p = h/mv$ Synoptic Link with Nuclear Physics

IMPORTANT NOTE

These equations must be memorised by students.

You will be tested on these equations.

The Language of Measurement

The following subject specific vocabulary provides definitions of key terms used in the A-level Science specifications.

Accuracy
A measurement result is considered accurate if it is judged to be close to the true value.

Calibration
Marking a scale on a measuring instrument.
This involves establishing the relationship between indications of a measuring instrument and standard or reference quantity values, which must be applied.
For example, placing a thermometer in melting ice to see whether it reads 0 °C, to check if it has been calibrated correctly.

Data
Information, either qualitative or quantitative, that has been collected.

Errors
See also uncertainties.

Measurement error
The difference between a measured value and the true value.
anomalies
These are values in a set of results which are judged not to be part of the variation caused by random uncertainty.

Random error
These cause readings to be spread about the true value, due to results varying in an unpredictable way from one measurement to the next.
Random errors are present when any measurement is made and cannot be corrected. The effect of random errors can be reduced by making more measurements and calculating a new mean.

Systematic error
These cause readings to differ from the true value by a consistent amount each time a measurement is made.
Sources of systematic error can include the environment, methods of observation or instruments used.
Systematic errors cannot be dealt with by simple repeats. If a systematic error is suspected, the data collection should be repeated using a different technique or a different set of equipment, and the results compared.

Zero error
Any indication that a measuring system gives a false reading when the true value of a measured quantity is zero, e.g. the needle on an ammeter failing to return to zero when no current flows.
A zero error may result in a systematic uncertainty.

Evidence
Data which has been shown to be valid.

Fair test
A fair test is one in which only the independent variable has been allowed to affect the dependent variable.

Hypothesis
A proposal intended to explain certain facts or observations.

Interval
The quantity between readings, e.g. a set of 11 readings equally spaced over a distance of 1 metre would give an interval of 10 centimetres.

Precision
Precise measurements are ones in which there is very little spread about the mean value. Precision depends only on the extent of random errors – it gives no indication of how close results are to the true value.

Prediction
A prediction is a statement suggesting what will happen in the future, based on observation, experience or a hypothesis.

Range
The maximum and minimum values of the independent or dependent variables; important in ensuring that any pattern is detected.
For example, a range of distances may be quoted as either:
'From 10 cm to 50 cm'
or
'From 50 cm to 10 cm'

Repeatable
A measurement is repeatable if the original experimenter repeats the investigation using same method and equipment and obtains the same results.

Reproducible
A measurement is reproducible if the investigation is repeated by another person, or by using different equipment or techniques, and the same results are obtained.

Resolution
This is the smallest change in the quantity being measured (input) of a measuring instrument that gives a perceptible change in the reading.

Sketch graph
A line graph, not necessarily on a grid, that shows the general shape of the relationship between two variables. It will not have any points plotted and although the axes should be labelled they may not be scaled.

True value
This is the value that would be obtained in an ideal measurement.

Uncertainty
The interval within which the true value can be expected to lie, with a given level of confidence or probability, e.g. "the temperature is 20 °C ± 2 °C, at a level of confidence of 95%.

Validity
Suitability of the investigative procedure to answer the question being asked. For example, an investigation to find out if the rate of a chemical reaction depended upon the concentration of one of the reactants would not be a valid procedure if the temperature of the reactants was not controlled.

Valid conclusion
A conclusion supported by valid data, obtained from an appropriate experimental design and based on sound reasoning.

Variables
These are physical, chemical or biological quantities or characteristics.

Categoric variables
Categoric variables have values that are labels. E.g. names of plants or types of material.

Continuous variables
Continuous variables can have values (called a quantity) that can be given a magnitude either by counting (as in the case of the number of shrimp) or by measurement (e.g. light intensity, flow rate etc.).

Control variables
A control variable is one which may, in addition to the independent variable, affect the outcome of the investigation and therefore must be kept constant or at least monitored.

Dependent variables
The dependent variable is the variable of which the value is measured for each change in the independent variable.

Independent variables
The independent variable is the variable for which values are changed or selected by the investigator.

IMPORTANT NOTE
These definitions must be memorised by students.

You will be tested on your knowledge of these definitions.

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: $hf = \phi + E_k$ (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.	

These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

NOTES

Observations

When light fell onto a metal plate it released electrons from the surface straight away. Increasing the intensity increased the number of electrons emitted.

If the frequency of the light was lowered, no electrons were emitted at all. Increasing the intensity and giving it more time did nothing, no electrons were emitted.

If Light was a Wave…

Increasing the intensity would increase the energy of the light. The energy from the light would be evenly spread over the metal and each electron would be given a small amount of energy. Eventually the electron would have enough energy to be removed from the metal.

Photon

Max Planck had the idea that light could be released in 'chunks' or packets of energy. Einstein named these wave-packets photons.

The energy carried by a photon is given by the equation:

$$E = hf$$

Since $c = f\lambda$ we can also write this as:

$$E = \frac{hc}{\lambda}$$

Explaining the Photoelectric Effect

Einstein suggested that one photon collides with one electron in the metal, giving it enough energy to be removed from the metal and then fly off somewhere. Some of the energy of the photon is used to break the bonds holding the electron in the metal and the rest of the energy is used by the electron to move away (kinetic energy).

He represented this with the equation:

$$hf = \phi + E_K$$

> **Tip**
>
> In this equation, kinetic energy and energy of a photon must be in Joules.
>
> Remember
>
> 1eV = 1.60 X 10^{-19}J

hf represents the energy of the photon, ϕ is the work function and E_K is the kinetic energy.

Work Function, ϕ

The work function is the amount of energy the electron requires to be completely removed from the surface of the metal. This is the minimum energy just to remove it, not to move away.

> **Tip**
>
> If the electron was just given the work function, it could not travel away from the metal.

Threshold Frequency, f_0

The threshold frequency is the minimum frequency that would release an electron from the surface of a metal, any less and nothing will happen.
Since $hf = \phi + E_K$, the minimum frequency releases an electron that is not moving, so $E_K = 0$

> Intensity does not affect photoemission below the threshold frequency.

$hf_0 = \phi$ which can be rearranged to give:

$$f_0 = \frac{\phi}{h}$$

Increasing the intensity increases the number of photons the light sources gives out each second.

If the photon has less energy than the work function an electron cannot be removed.

Increasing the intensity just sends out more photons, all of which would still not have enough energy to release an electron.

> Intensity only affects photoemission if the photons have energy above the threshold frequency.

Graph
If we plot a graph of the kinetic energy of the electrons against frequency, we get a graph that looks like this:
Start with $hf = \phi + E_K$ and transform into $y = mx + c$.

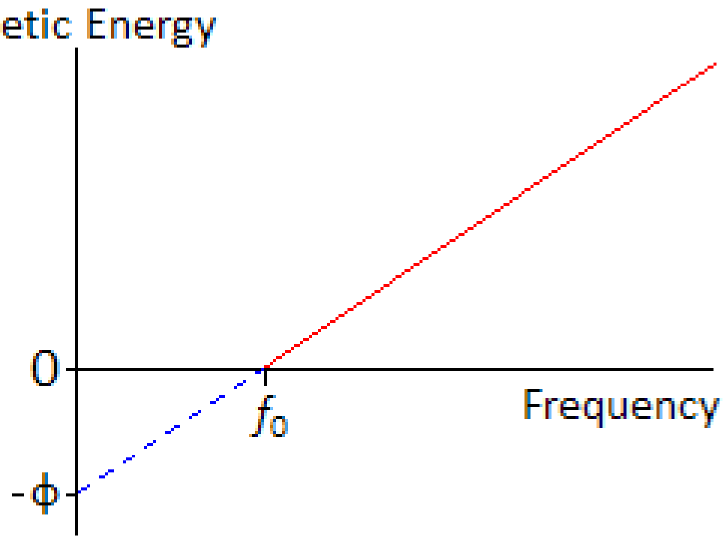
E_K is the y-axis and f is the x- axis.

This makes the equation become: $E_K = hf - \phi$

So the **gradient represents Planck's constant** and the **y-intercept represents (–) the work function**.

You must able to determine values from these graphs and include uncertainties in your values.

This graph must be a straight-line graph.



Nightclub Analogy
We can think of the photoelectric effect in terms of a full nightclub; let the people going into the club represent the photons, the people leaving the club represent the electrons and money represent the energy.

The club is full so it is one in and one out. The work function equals the entrance fee and is £5:
If you have £3 you don't have enough to get in so no one is kicked out.

If 50 people arrive with £3 no one has enough, so one gets in and no one is kicked out.

If you have £5 you have enough to get in so someone is kicked out, but you have no money for booze.

If 50 people arrive with £5 you all get in so 50 people are kicked out, but you have no money for booze.

If you have £20 you have enough to get in so someone is kicked out and you have £15 to spend on booze.

If 50 people arrive with £20 you all get in so 50 people are kicked out and you have £15 each to spend on booze.

Additional Note Space

Additional Note Space

REVISION SHEET

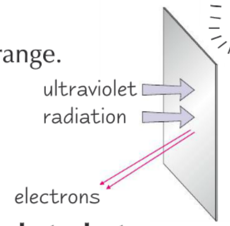
Highlight or underline the key information on the revision sheet to consolidate your understanding.

Shining Light on a Metal can Release Electrons

If you shine **light** of a **high enough frequency** onto the **surface of a metal**, the metal will **emit electrons**. For **most** metals, this **frequency** falls in the **UV** range.

'Light' means any EM radiation — not just visible light.

1) **Free electrons** on the **surface** of the metal **absorb energy** from the light.
2) If an electron **absorbs enough** energy, the **bonds** holding it to the metal **break** and the electron is **released**.
3) This is called the **photoelectric effect** and the electrons emitted are called **photoelectrons**.



You don't need to know the details of any experiments on this, you just need to learn the three main conclusions:

Conclusion 1 For a given metal, **no photoelectrons are emitted** if the radiation has a frequency **below** a certain value — called the **threshold frequency**.

Conclusion 2 The photoelectrons are emitted with a variety of kinetic energies ranging from zero to some maximum value. This value of **maximum kinetic energy** increases with the **frequency** of the radiation, and is **unaffected** by the **intensity** of the radiation.

Conclusion 3 The **number** of photoelectrons emitted per second is **proportional** to the **intensity** of the radiation.

These are the two that had scientists puzzled. They can't be explained using wave theory.

Intensity is the power (the energy transferred per second) hitting a given area of the metal (see page 31).

*The **Photoelectric Effect Couldn't** be Explained by **Wave Theory**...*

According to wave theory:

1) For a particular frequency of light, the **energy** carried is **proportional** to the **intensity** of the beam.
2) The energy carried by the light would be **spread evenly** over the wavefront.
3) **Each** free electron on the surface of the metal would gain a **bit of energy** from each incoming wave.
4) Gradually, each electron would gain **enough energy** to leave the metal.

SO... The **higher the intensity** of the wave, the **more energy** it should transfer to each electron — the kinetic energy should increase with **intensity**. There's **no explanation** for the **kinetic energy** depending only on the **frequency**.

There is also **no explanation** for the **threshold frequency**. According to **wave theory**, the electrons should be emitted **eventually**, no matter what the **frequency** is.

...But it **Could** be Explained by Einstein's **Photon Model of Light**

1) **Einstein** suggested that **EM waves** (and the energy they carry) **exist** in discrete packets — called **photons**.
2) The **energy carried** by one of these **photons** is:

$$E = hf = \frac{hc}{\lambda}$$

where h = Planck's constant = 6.63×10^{-34} Js
and c = speed of light in a vacuum = 3.00×10^{8} ms^{-1}

You might have seen this formula before on page 6.

3) Einstein saw these photons of light as having a **one-on-one**, **particle-like** interaction with **an electron** in a **metal surface**. A photon would **transfer all** its **energy** to **one**, **specific electron**.

According to the photon model:
1) When light hits its surface, the metal is **bombarded** by photons.
2) If one of these photons **collides** with a free electron, the electron will gain energy equal to hf.

Before an electron can **leave** the surface of the metal, it needs enough energy to **break the bonds holding it there**. This energy is called the **work function** (which has the symbol ϕ (phi)) and its **value** depends on the **metal**.

The **Photon Model** Explains the **Threshold Frequency**...

1) If the energy **gained** by an electron (on the surface of the metal) from a photon is **greater** than the **work function**, the electron is **emitted**.
2) If it **isn't**, the metal will heat up, but **no electrons** will be emitted.
3) Since, for **electrons** to be released, $hf \geq \phi$, the **threshold frequency** must be:

$$f = \frac{\phi}{h}$$

...and the **Maximum Kinetic Energy**

1) The **energy transferred** to an electron is hf.
2) The **kinetic energy** the electron will be carrying when it **leaves** the metal is hf **minus** any energy it's **lost** on the way out. Electrons **deeper** down in the metal lose more energy than the electrons on the **surface**, which explains the **range** of energies.
3) The **minimum** amount of energy it can lose is the **work function**, so the **maximum kinetic energy** of a photoelectron, $E_{k\,(max)}$, is given by the photoelectric equation:

$$hf = \phi + E_{k\,(max)} \quad \text{where} \quad E_{k\,(max)} = \frac{1}{2}mv_{max}^{2}$$

4) The **kinetic energy** of the electrons is **independent of the intensity** (the **number** of photons **per second** on an **area**, p.31), as they can **only absorb one photon** at a time. Increasing the **intensity** just means **more photons per second** on an **area** — each photon has the **same energy** as before.

The **Stopping Potential** Gives the **Maximum Kinetic Energy**

1) The **maximum kinetic energy** can be measured using the idea of **stopping potential**.
2) The **emitted electrons** are made to lose their energy by **doing work** against an applied **potential difference**.
3) The **stopping potential**, V_s, is the p.d. needed to stop the **fastest** moving electrons, with $E_{k\,(max)}$.
4) The **work done** by the p.d. in **stopping** the fastest electrons is equal to the **energy** they were carrying:

work done = p.d. × charge (see p.74)

$$eV_s = E_{k\,(max)}$$

where e = charge on the electron = 1.60×10^{-19} C, V_s = stopping potential in V, and $E_{k\,(max)}$ is measured in J.

Work done = zero.

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?

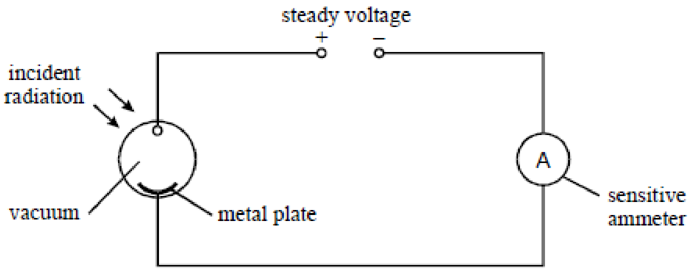
Q3. What is meant by the work function of the metal?

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.

SAMPLE QUESTION

S1. Discovery of the photoelectric effect was largely responsible for the development of the theory that electromagnetic radiation can behave as a particle or as a wave under different circumstances. The diagram below shows an experimental arrangement used to demonstrate aspects of the photoelectric effect. When photoelectrons are emitted the ammeter registers a current.



S1.1 The metal plate is illuminated with radiation but does not emit photoelectrons.

The intensity of the radiation is increased. State and explain what effect this increase in intensity has.

[2 Marks]

With an increase of intensity, no electrons will be released, there is no effect

1 mark

This is because the work function energy not being exceeded as insufficient photon energy to exceed work function, it is below the threshold frequency

1 mark

S1.2 The metal plate is illuminated with radiation such that photoelectrons are emitted. The intensity of the radiation is increased. State and explain what effect this increase in intensity has.

[2 Marks]

When an increase in intensity, there is more electrons released per second, so the current increases

1 mark

This is because there are more photons (above the threshold frequency) striking metal surface per second.

1 mark

S1.3 The metal plate is illuminated with radiation such that photoelectrons are emitted. Air is now allowed to enter the enclosure. State and explain what effect allowing air into the enclosure has.

[2 Marks]

Any of these are possible answers…

cause – 1 mark	**consequence – 1 mark**
electrons collide with air molecules	**less electrons reach anode per second**
photons absorbed by air	**less photons reach plate so fewer electrons emitted per second.**
air contaminates plate	**This increases the work function, so fewer photons sufficiently energetic to release electrons**
cause must be everything in one pair of boxes above	**ammeter reading or current falls**

S1.4 Show that the de Broglie wavelength of an electron travelling at 0.15*c* should be approximately 1.6×10^{-11} m.

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

[2 Marks]

$\lambda = \frac{h}{mv}$

$\lambda = 6.6 \times 10^{-34} / (3.0 \times 10^{8} \times 0.15 \times 9.1 \times 10^{-31})$

$\lambda = 1.61 \times 10^{-11}$ **m**

S1.5 Suggest a suitable material to give an observable diffraction pattern with electrons. Explain your choice.

[2 Marks]

crystal (or named crystalline material) / graphite

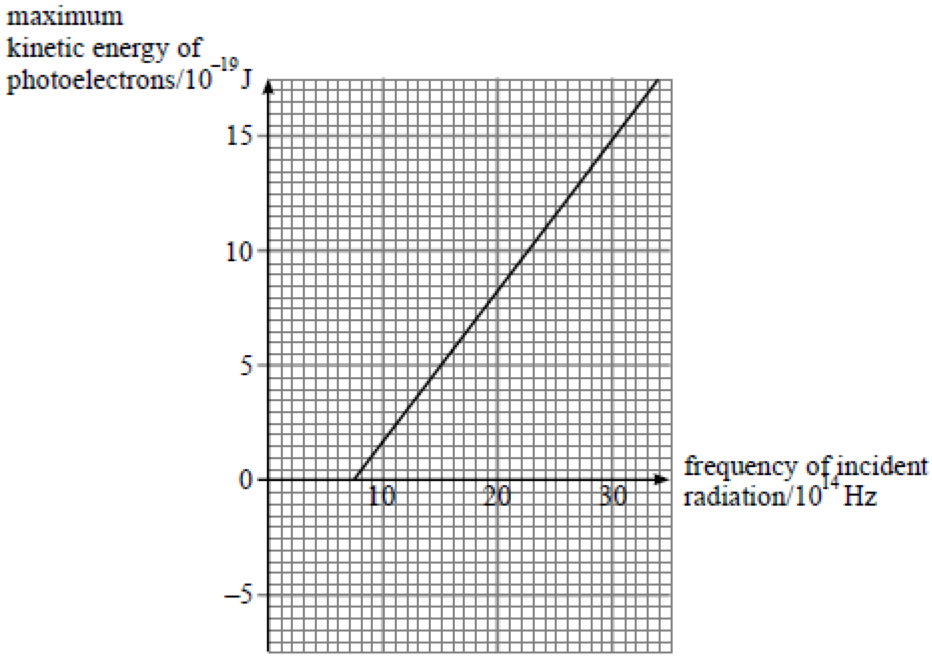
1 mark

as there is atomic spacing ≈ λ electrons

1 mark

SELF ASSESSMENT

A1. In the photoelectric effect, electrons are emitted from a metal surface when it is irradiated with electromagnetic radiation. The graph below shows the variation of the maximum photoelectron kinetic energy with the frequency of the radiation incident on the emitting surface.



A1.1 Use the data from the graph to calculate the Planck constant.

[3 Marks]

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....

A1.2 Determine the minimum energy required to remove an electron from the target metal.

[2 Marks]

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A1.3 Explain how the photoelectric effect produces evidence which illustrates the particulate nature of light.

[3 Marks]

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Reference: AQA A Level Physics Legacy B Examinations

A2. In the photoelectric effect, electromagnetic radiation incident on a metal surface causes electrons to be emitted from the surface.

A2.1 State and explain one aspect of the photoelectric effect that suggests the existence of photons.

[2 Marks]

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Ultra-violet radiation of wavelength 320 nm falls on a sodium surface.

Sodium has a **work function** of 3.7×10^{-19} J.

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

the Planck constant, h = 6.6×10^{-34} J s

mass of an electron, m_e = 9.1×10^{-31} kg

A2.2 State what is meant by the *work function* of a surface.

[2 Marks]

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A2.3 Show that the maximum kinetic energy of the electrons emitted from the sodium due to the incident ultra-violet radiation is about 2.5×10^{-19} J.

[2 Marks]

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A2.4 Determine the de Broglie wavelength associated with the emitted electrons.

[3 Marks]

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Reference: AQA A Level Physics Legacy B Examinations

A3. The photoelectric effect is one piece of evidence that suggests that light behaves like a stream of particles or photons.

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

[2 Marks]

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

[2 Marks]

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....

In an experiment to investigate the photoelectric effect the radiation incident on the surface caused the emission of electrons of energy 1.5×10^{-19} J.

The work function of the surface was known to be 3.2×10^{-19} J.

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

3.3 Calculate the wavelength of the incident radiation.

[2 Marks]

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3.4 Calculate the de Broglie wavelength of the emitted electrons.

[3 Marks]

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Reference: AQA A Level Physics Legacy B Examinations

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.	

These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

NOTES

The Electronvolt, eV

The Joule is too big use on an atomic and nuclear scale so we will now use the electronvolt, represented by eV.

One electronvolt is equal to the energy gained by an electron of charge *e*, when it is accelerated through a potential difference of 1 volt.

$1eV = 1.6 \times 10^{-19}J$ $1J = 6.25 \times 10^{18}eV$

eV → J multiply by *e* J → eV divide by *e*

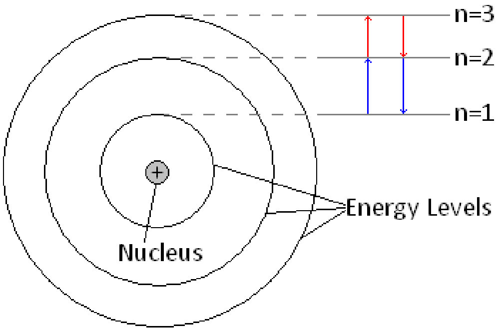
Learn the joule and electronvolt conversion equations for examinations.

The Problem with Atoms

Rutherford's nuclear model of the atom leaves us with a problem: a charged particle emits radiation when it accelerates. This would mean that the electrons would fall into the nucleus.

Bohr to the Rescue

Niels Bohr solved this problem by suggesting that the electrons could only orbit the nucleus in certain 'allowed' energy levels. He suggested that an electron may only transfer energy when it moves from one energy level to another. A change from one level to another is called a 'transition'.



To move up and energy level the electron must gain the **exact amount** of energy to make the transition.

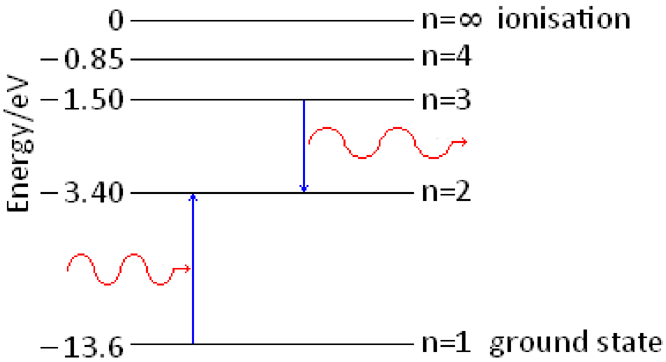
It can do this by another electron colliding with it or by absorbing a photon of the exact energy.

When moving down a level the electron must lose the exact amount of energy when making the transition.

It releases this energy as a photon of energy equal to the energy it loses.

$$\Delta E = hf = E_1 - E_2$$

E_1 is the energy of the level the electron starts at and E_2 is the energy of the level the electron ends at



Excitation
When an electron **gains the exact amount** of energy to move up one or more energy levels.

De-excitation
When an electron **gives out the exact amount** of energy to move back down to its original energy level.

If the exact amount of energy is not received, then nothing will happen.

Ionisation
An electron can gain enough energy to be completely removed from the atom.

The ground state and the energy levels leading up to ionisation have negative values of energy, this is because they are compared to the ionisation level.

Remember that energy must be given to the electrons to move up a level and is lost (or given out) when it moves down a level.

Ionisation can be considered an extreme form of excitation, if the energy given to the atom is much larger than the ionisation energy level, the electron will leave the atom and the atom will become ionised.

Additional Note Space

PUZZLES QUESTIONS

To improve your understanding, answer the following puzzles.

The answers are overleaf.

1 Define the electron volt.

2 Suppose a certain atom emits a photon of wavelength 683.8 nm. How much energy does the atom lose?

3 Energy level diagram for the hydrogen atom.

Energy level	Quantum number	Energy/eV
E_∞	∞	0
E_5	5	−0.54
E_4	4	−0.85
E_3	3	−1.5
E_2	2	−3.4
E_1	1	−13.6

Convert the energy levels into joules. Calculate all the possible wavelengths that can be produced and sort them into different parts of the em spectrum.

4 The visible spectrum extends from 400 nm to 750 nm. Are all lines in the Balmer series in the hydrogen spectrum visible?

5 What energy do electrons require to lift a hydrogen atom from the ground state to its second excitation level? Give your answer in both electron volts and joules.

6 Explain the term 'excitation potential'.

7 What are the chief characteristics of a line spectrum?

8 What assumptions did Bohr make which led to the idea of energy levels?

9 Why are energy levels given in negative values?

Working Out Space

ANSWERS

2 2.89×10^{-19} J.

3 $E_5 = -0.871 \times 10^{-19}$ J
$E_4 = -1.36 \times 10^{-19}$ J
$E_3 = -2.42 \times 10^{-19}$ J
$E_2 = -5.45 \times 10^{-19}$ J
$E_1 = -21.79 \times 10^{-19}$ J

Lyman series (all jumps down to E_1): 122 nm, 103 nm, 97.5 nm, 95.21 nm, 91.2 nm
Balmer series (all jumps down to E_2): 656 nm, 486 nm, 434 nm, 365 nm
Paschen series (all jumps down to E_3): 1880 nm, 1280 nm, 822 nm
Brackett series (all jumps down to E_4): 4060 nm, 1460 nm
2312 nm

4 No, 364 nm is not.

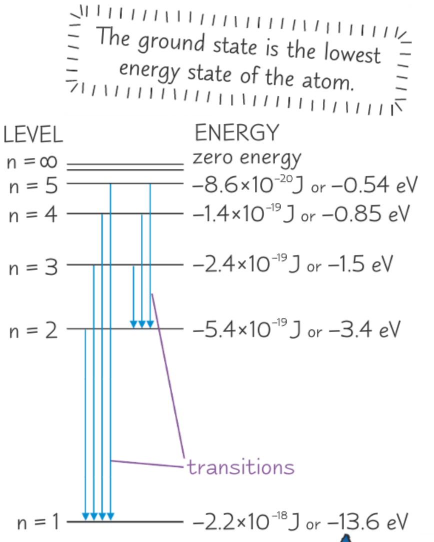
5 12.1 eV, 19.4×10^{-19} J

REVISION

Highlight or underline the key information on the revision sheet to consolidate your understanding.

Electrons in *Atoms* Exist in *Discrete Energy Levels*

1) **Electrons** in an **atom** can **only exist** in certain **well-defined energy levels**. Each level is given a **number**, with **n = 1** representing the **ground state**.
2) Electrons can **move down** energy levels by **emitting** a **photon**.
3) Since these **transitions** are between **definite energy levels**, the **energy** of **each photon** emitted can **only** take a **certain allowed value**.
4) The diagram on the right shows the **energy levels** for **atomic hydrogen**.
5) The **energies involved** are **so tiny** that it makes sense to use a more **appropriate unit** than the **joule**. The **electronvolt (eV)** is defined as:



The **kinetic energy carried** by an **electron** after it has been **accelerated** through a **potential difference** of **1 volt**.

energy gained by electron (eV) = accelerating voltage (V)

1 eV = 1.60 × 10^{-19} J

The energies are only negative because of how "zero energy" is defined. Just one of those silly convention things — don't worry about it.

6) On the diagram, energies are labelled in **both units** for **comparison's** sake.
7) The **energy** carried by each **photon** is **equal** to the **difference in energies** between the **two levels**. The equation below shows a **transition** between a higher energy level n = 2 where the electrons have energy E_2 and a lower energy level n = 1 with electrons of energy E_1:

$$\Delta E = E_2 - E_1 = hf = \frac{hc}{\lambda}$$

8) Electrons can also **move up** energy levels if they **absorb a photon** with the **exact energy difference** between the two levels. The movement of an electron to a higher energy level is called **excitation**.
9) If an electron is **removed** from an atom, we say the atom is **ionised**. The energy of each **energy level** within an atom gives the amount of **energy** needed to **remove an electron** in that level from the atom. The **ionisation energy** of an atom is the amount of energy needed to completely remove an electron from the atom from the **ground state** (**n = 1**).

Reference: CGP Revision Guide

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?

SAMPLE QUESTION

S1. When free electrons collide with atoms in their *ground state*, the atoms can be excited or ionised.

S1.1 State what is meant by ground state.

[1 Mark]

when electrons/atoms are in their lowest/minimum energy (state) or most stable (state) they (are in their ground state).

S1.2 Explain the difference between excitation and ionisation.

[3 Marks]

In either case an electron receives (exactly the right amount of) energy

1 mark

excitation promotes an (orbital) electron to a higher energy level

1 mark

ionisation occurs when an electron receives enough energy to leave the atom

1 mark

S1.3 An atom can also become excited by the absorption of photons. Explain why only photons of certain frequencies cause excitation in a particular atom.

[4 Marks]

electrons occupy discrete energy levels

1 mark

and need to absorb an exact amount of energy to move to a higher level

1 mark

photons need to have certain frequency to provide this energy or $E = hf$

1 mark

energy required is the same for a particular atom but different for other elements

1 mark

When collisions occur all energy of photon absorbed, removing the photon

1 mark

S1.4 The ionisation energy of hydrogen is 13.6 eV. Calculate the minimum frequency necessary for a photon to cause the ionisation of a hydrogen atom. Give your answer to an appropriate number of significant figures.

[4 Marks]

Convert the energy from eV into Joules

energy = $13.6 \times 1.60 \times 10^{-19} = 2.176 \times 10^{-18}$ J

$hf = 2.176 \times 10^{-18}$

$f = 2.176 \times 10^{-18} \div 6.63 \times 10^{-34} = 3.28 \times 10^{15}$ Hz

This answer must be given to the correct sig figs (3).

(Total 12 marks)

Reference: AQA A Level Physics January 2012 Unit 1 Examinations

SELF ASSESSMENT

A1. A fluorescent tube is filled with mercury vapour at low pressure. After mercury atoms have been excited they emit photons.

A1.1 In which part of the electromagnetic spectrum are these photons?

[1 Mark]

……

……

A1.2 What is meant by an excited mercury atom?

[1 Mark]

……

……

A1.3 How do the mercury atoms in the fluorescent tube become excited?

[2 Marks]

……

……

……

……

A1.4 Why do the excited mercury atoms emit photons of characteristic frequencies?

[3 Marks]

……

……

……

……

The wavelength of some of the photons emitted by excited mercury atoms is 254 nm.

A1.5 Calculate the frequency of the photons.

[2 Marks]

……

……

frequency ………………………………… Hz

A1.6 Calculate the energy of the photons in electron volts (eV).

[2 Marks]

....

....

energy .... eV

A1.7 Explain how the coating on the inside of a fluorescent tube emits visible light.

[2 Marks]

....

....

....

....

Reference: AQA A Level Physics June 2014 Unit 1 Examinations

A2. A fluorescent tube is filled with mercury vapour at low pressure. In order to emit electromagnetic radiation the mercury atoms must first be *excited*.

A2.1 What is meant by an excited atom?

[1 Mark]

....

....

A2.2 Describe the process by which mercury atoms become excited in a fluorescent tube.

[3 Marks]

....

....

A2.3 What is the purpose of the coating on the inside surface of the glass in a fluorescent tube?

[3 Marks]

....

....

....

Reference: AQA A Level Physics June 2012 Unit 1 Examinations

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. $hf = E_1 - E_2$	
Observation of line spectra using a diffraction grating.	

NOTES

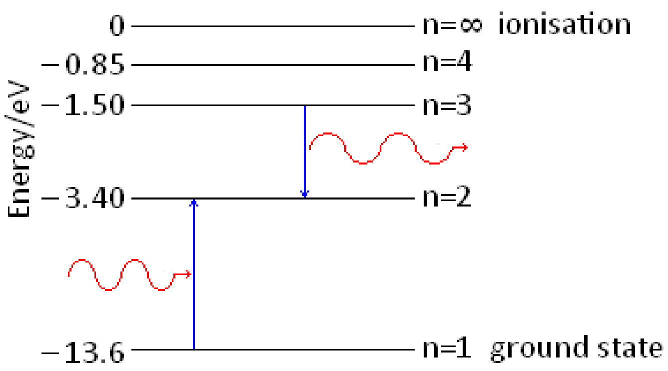
These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

Bohr's atom

Niels Bohr suggesting that the electrons cou levels. He suggested that an electron may only transfer energy when it moves from one energy level to another. A change from one level to another is called a 'transition'.



The energy levels tend to be given in 'negative values' as this is the amount of energy which the electron needs to escape the nucleus attraction from this level.

If an electron is on an energy level it does not gain or lose any energy.

To move up and energy level the electron must gain the exact amount of energy to make the transition.

It can do this by another electron colliding with it or by absorbing a photon of the exact energy.

When moving down a level the electron must lose the exact amount of energy when making the transition.

It releases this energy as a photon of energy equal to the energy it loses.

$$\Delta E = hf = E_1 - E_2$$

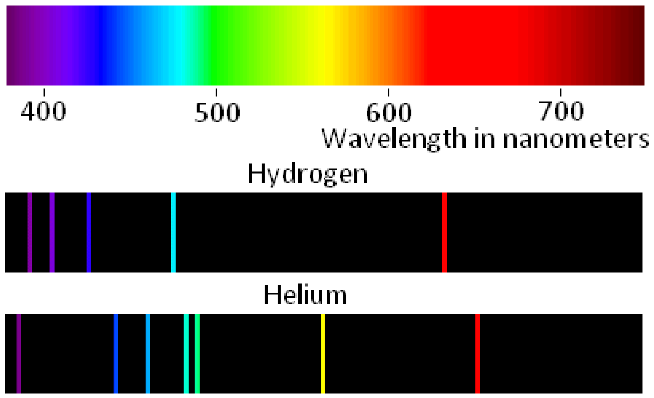
E_1 is the energy of the level the electron starts at and E_2 is the energy of the level the electron ends at

Line Spectra

Atoms of the same element have same energy levels. Each transition releases a photon with a set amount of energy meaning the frequency and wavelength are also set. The wavelength of light is responsible for colour it is.

We can analyse the light by using a diffraction grating to separate light into the colours that makes it up, called its **line spectra.** Each element has its own line spectra like a barcode.

Below is the line spectra of Hydrogen and Helium.



Emission spectra are the lines which are caused by the energies needed to cause excitation.

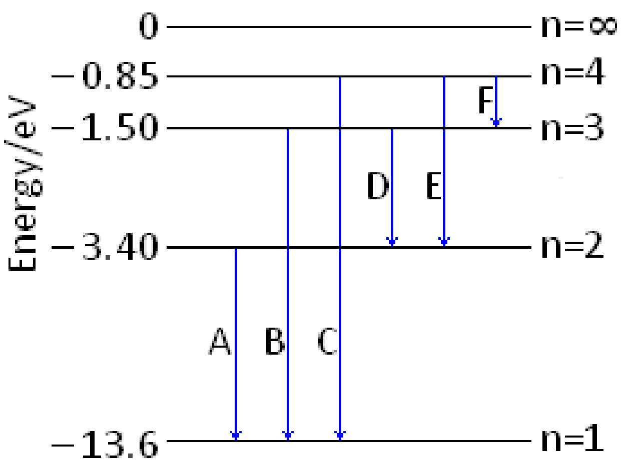
Absorption spectra are the lines which caused by the energies produced in de-excitation.

We can calculate the energy difference that created the colour.

If we know the energy differences for each element we can work out which element is responsible for the light and hence deduce which elements are present.

We can see that there are 6 possible transitions in the diagram to the left, A to F.

D has an energy difference of 1.9 eV or 3.04 x 10^{-19} J which corresponds to a frequency of 4.59 x 10^{14} Hz and a wavelength of 654 nm – red.



Emission and absorption spectra tend to have many lines as there are many possible transitions between the different energy levels.

This makes each spectra unique for each element.

Additional Note Space

REVISION

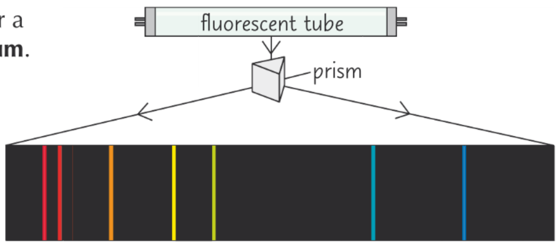
Highlight or underline the key information on the revision sheet to consolidate your understanding.

Fluorescent Tubes use Excited Electrons to Produce Light

1) **Fluorescent tubes** contain **mercury vapour**, across which an initial **high voltage** is applied. This **high voltage** accelerates **fast-moving free electrons** that **ionise** some of the **mercury atoms**, producing **more** free electrons.
2) When this flow of free electrons **collides** with electrons in **other mercury atoms**, the electrons in the mercury atoms are **excited** to **higher energy levels**.
3) When these **excited electrons** return to their **ground states**, they emit **photons** in the **UV** range.
4) A **phosphorus coating** on the **inside** of the tube **absorbs** these **photons**, exciting its **electrons** to **much higher orbits**. These electrons then **cascade** down the **energy levels**, **emitting** many **lower energy photons** in the form of **visible light**.

Fluorescent Tubes Produce Line Emission Spectra

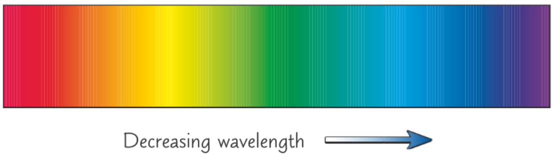
1) If you **split** the light from a **fluorescent tube** with a **prism** or a **diffraction grating** (see pages 34-35), you get a **line spectrum**.
2) A line spectrum is seen as a **series** of **bright lines** against a **black background**.
3) Each **line** corresponds to a **particular wavelength** of light **emitted** by the source.
4) Since only certain photon energies are allowed, you only see the **wavelengths** corresponding to these energies.



Shining White Light through a Cool Gas gives an Absorption Spectrum

Continuous Spectra Contain All Possible Wavelengths

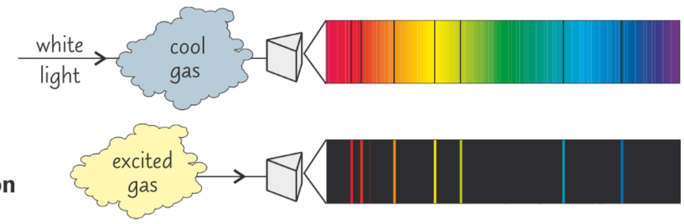
1) The **spectrum** of **white light** is **continuous**.
2) If you **split** the **light** up with a **prism**, the **colours** all **merge** into each other — there **aren't** any **gaps** in the spectrum.
3) **Hot things** emit a **continuous spectrum** in the visible and infrared.



4) **All** the **wavelengths** are allowed because the electrons are **not confined** to **energy levels** in the object producing the **continuous spectrum**. The electrons are not bound to atoms and are **free**.

Cool Gases Remove Certain Wavelengths from the Continuous Spectrum

1) You get a **line absorption spectrum** when **light** with a **continuous spectrum** of **energy** (white light) passes through a cool gas.
2) At **low temperatures**, **most** of the **electrons** in the **gas atoms** will be in their **ground states**.
3) The electrons can only absorb **photons** with **energies** equal to the **difference** between **two energy levels**.
4) **Photons** of the **corresponding wavelengths** are **absorbed** by the **electrons** to **excite** them to **higher energy levels**.
5) These **wavelengths** are then **missing** from the **continuous spectrum** when it **comes out** the other side of the gas.
6) You see a **continuous spectrum** with **black lines** in it corresponding to the **absorbed wavelengths**.
7) If you **compare** the **absorption** and **emission spectra** of a **particular gas**, the **black lines** in the **absorption spectrum match up** to the **bright lines** in the **emission spectrum**.



Reference: CGP Revision Guide

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.

SAMPLE QUESTION

S1.

$E = 0$	____________	ionisation level
$E_2 = -2.42 \times 10^{-19}$ J	____________	level 2
$E_1 = -5.48 \times 10^{-19}$ J	____________	level 1
$E_0 = -2.18 \times 10^{-18}$ J	____________	ground state

The diagram represents some of the energy levels of an isolated atom.

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

S1.1 Calculate the speed of the electron just before the collision.

[2 Marks]

$E_k = 1/2mv^2$

Rearrange this to make v the subject

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

Give the answer to the correct sig figs.

$v = 2.1 \times 10^{6}$ m s^{-1}

Show that the electron can excite the atom to level 2.

[2 Marks]

difference between E_2 and E_0 = 1.94×10^{-18} J

1 mark

which is less than the electron kinetic energy, this makes it possible to be excited.

1 mark

S1.2 Calculate the wavelength of the radiation that will result when an atom in level 2 falls to level 1 and state the region of the spectrum to which this radiation belongs.

[4 Marks]

$\Delta E = (E_2 - E_1)$

$\Delta E = 3.06 \times 10^{-19}$

$\Delta E = \frac{hc}{\lambda}$

$$\lambda = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}{3.06 \times 10^{-19}}$$

$\lambda = 6.5 \times 10^{-7}$ m

This is roughly in visible region

S1.3 Calculate the minimum potential difference through which an electron must be accelerated from rest in order to be able to ionise an atom in its ground state with the above energy level structure.

[2 Marks]

Potential Difference = Energy / Charge

Ionisation, p.d. = $\frac{21.8 \times 10^{-19}}{1.6 \times 10^{-19}}$

Ionisation p.d.=13.6 V

(Total 10 marks)

Reference: AQA A Level Physics Legacy A Examinations

SELF ASSESSMENT

A1.1 State what happens in an atom when line spectra are produced.

[2 Marks]

....

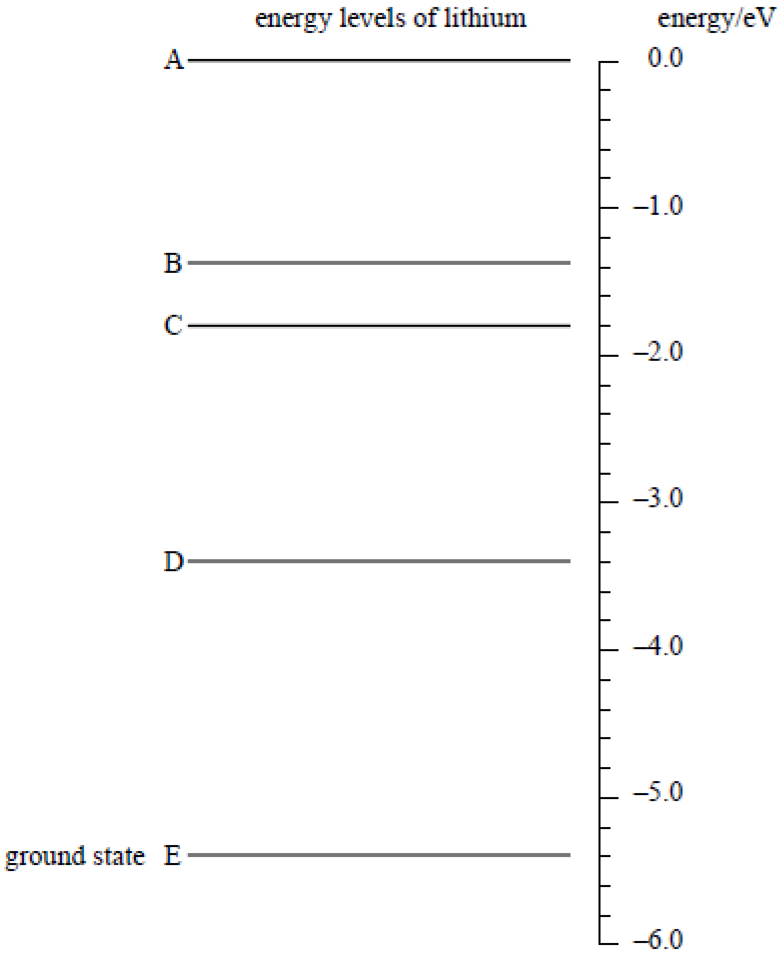
....

....

....

The diagram below represents some energy levels of the lithium atom.

[7 Marks]



A1.2 Calculate the ionisation energy, in J, of the lithium atom.

....

....

A1.3 An excited lithium atom may emit radiation of wavelength 6.1×10^{-7} m.

Show that the frequency of this radiation is approximately 5.0×10^{14} Hz.

....

....

A1.4 Calculate the energy, in J, of each photon of this radiation.

....

....

A1.5 Draw, on the diagram, an arrow between two energy levels which shows the transition responsible for the emission of a photon of energy 2.0 eV.

A1.6 Two transitions emit radiation of similar frequencies. One of them is the transition between A and C. What is the other?

....

....

A1.7 A transition between which two levels would give radiation of the longest possible wavelength?

....

....

Reference: AQA A Level Physics Legacy A Examinations

A2.1 Describe how the concept of *energy levels* is useful in the explanation of **line spectra.**

[3 Marks]

....

....

....

....

....

....

The diagram represents some energy levels of the mercury atom.

[7 Marks]

________________________________ 0

________________________________ –1.6 eV

________________________________ –3.7 eV

________________________________ –5.5 eV

________________________________ –10.4 eV ground state

Charge of electron = 1.6×10^{-19} C

The Planck constant = 6.6×10^{-34} J s

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

A2.2 What is the ionisation energy, in J, of the mercury atom?

....

....

A2.3 Determine which transition corresponds to the emission of radiation of wavelength 141 nm.

....

....

....

....

....

....

A2.4 State the region of the spectrum in which you would expect to find radiation of this wavelength.

....

....

A3. The diagram below shows some of the energy levels of the hydrogen atom.

energy/10^{-19}J

0 _____________________________ $n = \infty$

–2.4 _____________________________ $n = 3$

–5.4 _____________________________ $n = 2$

–22 _____________________________ $n = 1$ (ground state)

A3.1 Explain how changes of electron energies can produce a line emission spectrum.

[3 Marks]

....

....

....

....

A3.2 What is meant by *ionisation*?

....

....

A3.3 State the energy, in J, required to ionise a hydrogen atom from its ground state.

....

....

A3.4 Calculate the minimum frequency of radiation that can ionise a hydrogen atom from its ground state.

....

....

....

....

A3.5 Explain what happens to an electron in the ground state of a hydrogen atom when it receives radiation of a frequency greater than the minimum frequency obtained in part **A3.4**

....

....

[5 Marks]

A3.6 Calculate the wavelength of the radiation emitted when an electron falls from level $n = 3$ to level $n = 2$ in the hydrogen atom.

[3 Marks]

....

....

....

....

Reference: AQA A Level Physics Legacy A Examinations

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 λ = 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 tub[e]	

These notes are brief.

More detailed notes are found in the student preparatory reading book.

Please read the preparatory reading notes.

NOTES
De Broglie
In 1923 Louis de Broglie put forward the idea that 'all particles have a wave nature' meaning that particles can behave like waves.

This doesn't sound too far-fetched after Einstein proved that a wave can behave like a particle.

De Broglie said that all particles could have a wavelength. A particle of mass, *m*, that is travelling at velocity, *v*, would have a wavelength given by:

$$\lambda = \frac{h}{mv}$$

which is sometime written as

$$\lambda = \frac{h}{p}$$

where *p* is momentum

This was the first equation which linked the quantum world with the macroscopic world.

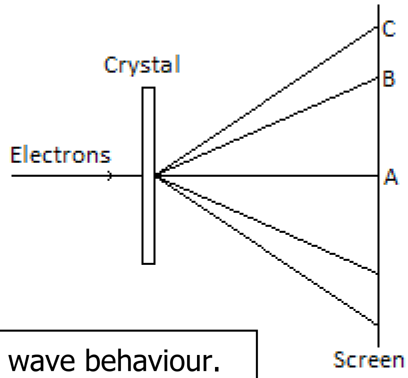
This wavelength is called the de Broglie wavelength.
The modern view is that the de Broglie wavelength is linked to the probability of finding the particle at a certain point in space.

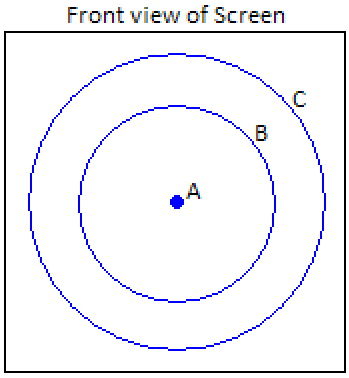
De Broglie wavelength is measured in metres, m

Electron Diffraction

Two years after de Broglie came up with his particle wavelengths and idea that electrons could diffract, Davisson and Germer proved this to happen.

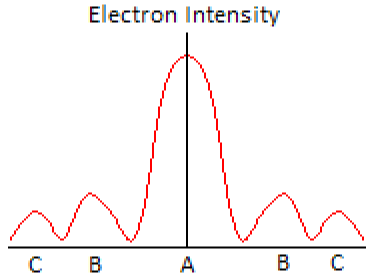
They fired electrons into a crystal structure which acted as a diffraction grating. This produced areas of electrons and no electrons on the screen behind it, just like the pattern you get when light diffracts.





Diffraction is evidence of wave behaviour.

If an object exhibits wave behaviour, it must have a wavelength.



Electron Wavelength

We can calculate the de Broglie wavelength of an electron from the potential difference, *V*, that accelerated it.

Change in electric potential energy gained = eV

This is equal to the kinetic energy of the electron $eV = \frac{1}{2}mv^2$

The velocity is therefore given by: $\sqrt{\frac{2eV}{m}} = v$

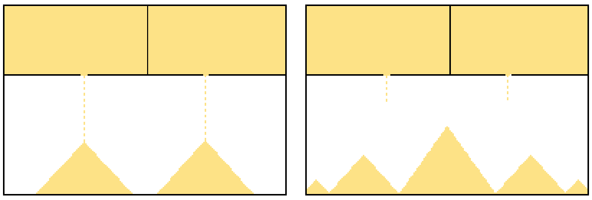
We can substitute this into $\lambda = \frac{h}{mv}$ to get:

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

Sand Analogy
If we compare a double slit electron diffraction to sand falling from containers we can see how crazy electron diffraction is.

Imagine two holes about 30cm apart that sand is dropping from.

We would expect to find a maximum amount of sand under each hole, right? This is not what we find! We find a maximum in between the two holes. The electrons are acting like a wave.



Wave-Particle Duality
Wave-particle duality means that waves sometimes behave like particles and particles sometimes behave like waves. Some examples of these are shown below:

Light as a Wave
Diffraction, interference, polarisation and refraction all prove that light is a wave and will be covered in waves unit.

Light as a Particle
We have seen that the photoelectric effect shows that light can behave as a particle called a photon.

Electron as a Particle
The deflection by an electromagnetic field and collisions with other particles show its particle nature.

Electron as a Wave
Electron diffraction proves that a particle can show wave behaviour .

Additional Note Space

Additional Note Space

PUZZLES QUESTIONS

To improve your understanding, answer the following puzzles.

The answers are overleaf.

1 Calculate the momentum of a photon of light of wavelength 5.0×10^{-7} m.

2 How many photons of light are emitted every second from a 60 W light bulb of efficiency 11%? (This means that only 11% of 60 W is emitted in the form of light.) Assume that the average wavelength of the light emitted is 5.0×10^{-7} m.

3 On the Earth the Sun provides 1400 W of power per square metre. The range of wavelengths stretches from infrared to ultraviolet. Making the rather large assumption that the average wavelength is 1.0×10^{-6} m, calculate

(a) the momentum of one photon of this wavelength

(b) the number of photons striking one square metre of the Earth every second

(c) the rate of change of momentum of these photons, assuming they are all absorbed

(d) the force on each square metre of the vanes of a satellite at this distance from the Sun and facing the Sun

(e) the area of vanes required for the satellite, of mass 2800 kg, if it is to have an acceleration away from the Sun of 0.008 m s^{-2}.

4 Calculate the wavelength of an electron travelling at 3.2×10^{7} m s^{-1}. The mass of an electron is 9.1×10^{-31} kg; the Planck constant is 6.6×10^{-34} J s.

5 An electron is accelerated by a potential difference of 3000 V before striking a layer of graphite in which the atoms are separated by a distance of 1.6×10^{-10} m. Calculate the angles of diffraction for both the first and second order diffraction circles. (Hint: apply the diffraction equation $n\lambda = d \sin\theta$.)

Working Out Space

ANSWERS

1 1.32×10^{-27} N s

2 1.7×10^{19}

3 (a) 6.6×10^{-28} N s
(b) 7.1×10^{21}
(c) 4.7×10^{-6} N
(d) 4.7×10^{-6} N
(e) 4 800 000 m^2

4 2.3×10^{-11} m

5 8.0°, 16.2°

REVISION

Highlight or underline the key information on the revision sheet to consolidate your understanding.

Interference and Diffraction show Light as a Wave

1) Light produces **interference** and **diffraction** patterns — **alternating bands** of **dark** and **light**.
2) These can **only** be explained using **waves interfering constructively** (when two waves overlap in phase) or **interfering destructively** (when the two waves are out of phase). (See p.26.)

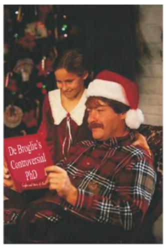
The Photoelectric Effect Shows Light Behaving as a Particle

1) **Einstein** explained the results of **photoelectricity experiments** (see p.16) by thinking of the **beam of light** as a series of **particle-like photons**.
2) If a **photon** of light is a **discrete** bundle of energy, then it can **interact** with an **electron** in a **one-to-one way**.
3) **All** the **energy** in the **photon** is **given** to one **electron**.

De Broglie Came Up with the Wave-Particle Duality Theory

1) Louis de Broglie made a **bold suggestion** in his **PhD thesis**:

> If '**wave-like**' **light** showed **particle properties** (photons), '**particles**' like **electrons** should be expected to show **wave-like properties**.



I'm not impressed — this is just speculation. What do you think, Dad?

2) The **de Broglie equation** relates a **wave property** (**wavelength**, λ) to a **moving particle property** (**momentum**, mv). h = Planck's constant = 6.63×10^{-34} Js.

This is called the de Broglie wavelength.

$$\lambda = \frac{h}{mv}$$

3) The **de Broglie wave** of a particle can be interpreted as a '**probability wave**'.
(The probability of finding a particle at a point is directly proportional to the square of the amplitude of the wave at that point — but you don't need to know that for your exam.)
4) Many physicists at the time **weren't very impressed** — his ideas were just **speculation**. But later experiments **confirmed** the wave nature of electrons.

Electron Diffraction shows the Wave Nature of Electrons

1) **Diffraction patterns** are observed when **accelerated electrons** in a vacuum tube **interact** with the **spaces** in a graphite **crystal**.
2) This **confirms** that electrons show **wave-like** properties.
3) According to wave theory, the **spread** of the **lines** in the diffraction pattern **increases** if the **wavelength** of the wave is **greater**.
4) In electron diffraction experiments, a **smaller accelerating voltage**, i.e. **slower** electrons, gives more **widely-spaced** rings.
5) **Increase** the **electron speed** (and therefore the electron **momentum**) and the diffraction pattern circles **squash together** towards the **middle**. This fits in with the **de Broglie** equation above — if the **momentum** is **greater**, the **wavelength** is **shorter** and the **spread** of the lines is **smaller**.

> In general, λ for **electrons** accelerated in a **vacuum tube** is about the **same size** as **electromagnetic waves** in the **X-ray** part of the spectrum.

6) If particles with a **greater mass** (e.g. **neutrons**) were travelling at the **same speed** as the electrons, they would show a more **tightly-packed diffraction pattern**. That's because a neutron's **mass** (and therefore its **momentum**) is **much greater** than an electron's, and so a neutron has a **shorter de Broglie wavelength**.

Particles Don't show Wave-Like Properties All the Time

You **only** get **diffraction** if a particle interacts with an object of about the **same size** as its **de Broglie wavelength**. A **tennis ball**, for example, with **mass 0.058 kg** and **speed 100 ms^{-1}** has a **de Broglie wavelength** of **10^{-34} m**. That's **10^{19} times smaller** than the **nucleus** of an **atom**! There's nothing that small for it to interact with.

Example: An electron of mass 9.11×10^{-31} kg is fired from an electron gun at 7.00×10^{6} ms^{-1} (to 3 s.f.). What size object will the electron need to interact with in order to diffract?

Momentum of electron = $mv = (9.11 \times 10^{-31}) \times (7.00 \times 10^{6}) = 6.377 \times 10^{-24}$ kg ms^{-1}

$\lambda = h/mv = 6.63 \times 10^{-34} / 6.377 \times 10^{-24} = 1.0396... \times 10^{-10} =$ **1.04×10^{-10} m (to 3 s.f.)**

Only crystals with atom layer spacing around this size are likely to cause the diffraction of this electron.

Wave-Particle Duality Wasn't Accepted Straight Away

De Broglie first **hypothesised** wave-particle duality to explain **observations** of light acting as both a particle and a wave. But his theory **wasn't accepted** straight away. **Other scientists** had to **evaluate** de Broglie's theory (by a process known as **peer review**) before he **published** it, and then it was **tested with experiments**. Once enough evidence was found to back it up, the theory was accepted as **validated** by the scientific community.

Scientists' understanding of the nature of matter has changed over time through this process of **hypothesis and validation**. De Broglie's theory is **accepted** to be true — that is, until any new conflicting evidence comes along.

Reference: CGP Revision Guide

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?

SAMPLE QUESTION

S1.1 Explain what is meant by the **duality** of electrons.

[2 Marks]

electrons behave sometimes as particles

1 mark

and sometimes as waves

1 mark

S1.2 State the relation between the electron mass, electron velocity and the wavelength for a monoenergetic beam of electrons.

[3 Marks]

$mu \propto 1 / \lambda$

As $mu = h / \lambda$

S1.3 The spacing of atoms in a crystal is 1.0×10^{-10} m.

[4 Marks]

mass of the electron = 9.1×10^{-31} kg
the Planck constant = 6.6×10^{-34} J s

Estimate the speed of electrons which would give detectable diffraction effects with such crystals.

For (crystal) diffraction, electron wavelength must be of order of atom spacing to get diffraction.

hence $\lambda \approx 10^{-10}$ **m – the approximate spacing between atoms.**

$$v = \frac{h}{m\lambda} \text{ (1) } = \frac{6.6 \times 10^{-34}}{9.1 \times 10^{-31} \times 10^{-10}} = 7.2(5) \times 10^{6} \text{ m s}^{-1}$$

S1.4 Give **one** piece of evidence to demonstrate that electrons have particle properties.

[1 Mark]

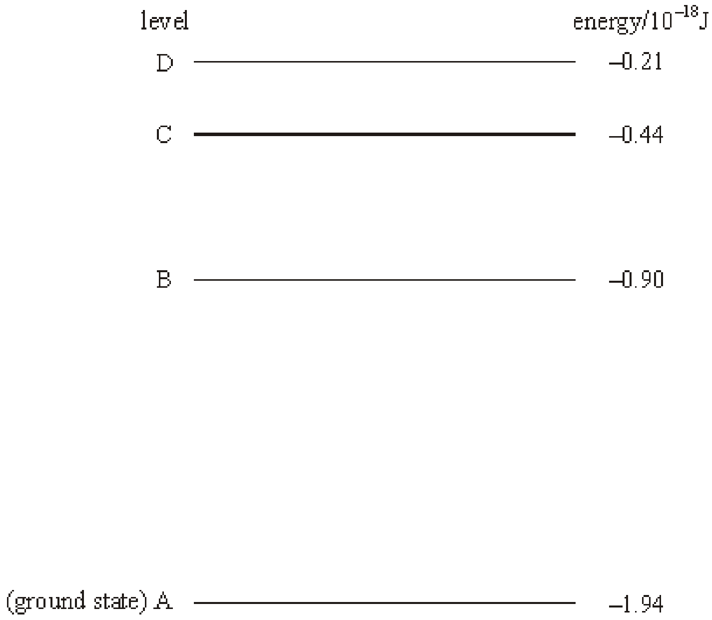
Electrons can be deflected in an electric field.

(Total 8 marks)

Reference: AQA A Level Physics Legacy A Examinations

SELF ASSESSMENT

A1. The diagram shows some of the electron energy levels of an atom.



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

For the incident electron, calculate

[4 Marks]

A1.1 the kinetic energy in eV,

....

....

A1.2 the de Broglie wavelength.

....

....

....

....

A1.3 When the excited electron returns directly from level D to level B it emits a photon.
Calculate the wavelength of this photon.

[3 Marks]

....

....

Reference: AQA A Level Physics Legacy A Examinations

A2. Electrons behave in two distinct ways. This is referred to as the **duality *of electrons*.**

[3 Marks]

A2.1 State what is meant by the duality of electrons.

....

....

A2.2 Give **one** example of each type of behaviour of electrons.

....

....

A2.3 Calculate the speed of electrons that have a de Broglie wavelength of 1.70×10^{-10} m.

[2 Marks]

....

....

....

....

Reference: AQA A Level Physics Legacy A Examinations

A3. Electrons travelling at a speed of 5.00×10^{5} m s^{-1} exhibit **wave properties.**

A3.1 What phenomenon can be used to demonstrate the wave properties of electrons?

Details of any apparatus used are not required.

[1 Mark]

....

....

A3.2 Calculate the wavelength of these electrons.

[2 Marks]

....

....

....

....

A3.3 Calculate the speed of muons with the same wavelength as these electrons.
Mass of muon = 207 × mass of electron

[3 Marks]

....

....

....

....

A3.4 Both electrons and muons were accelerated from rest by the same potential difference.

Explain why they have different wavelengths.

[2 Marks]

....

....

....

....

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}	$\mathrm{J\ s}$
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}	$\mathrm{m\ K}$
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 $$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

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

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

Electricity

current and pd	$I = \frac{\Delta Q}{\Delta t}$ $\quad V = \frac{W}{Q}$ $\quad R = \frac{V}{I}$
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	$\varepsilon = \frac{E}{Q}$ $\quad \varepsilon = I(R + r)$

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 $I_{rms} = \frac{I_0}{\sqrt{2}}$ $V_{rms} = \frac{V_0}{\sqrt{2}}$

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 $P = \sigma AT^4$

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 $I = \Sigma m r^2$

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 = (area of $p - V$ loop) × (number of cycles per second) × (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 $\frac{QV}{d} = mg$

$F = 6\pi\eta r v$

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.

This has been document has been produced for educational purposes only.

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

Student Voice

If you when using this document, you believe there is an improvement to made, please state this in the space below….

Only constructive and reasoned feedback will be considered.