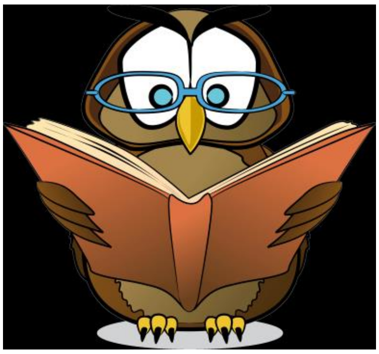
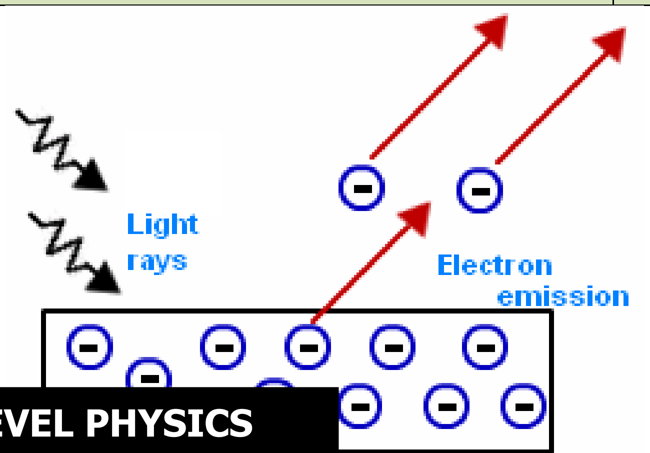


ST MARY'S SCIENCE DEPARTMENT: PHYSICS

A LEVEL PHYSICS **YEAR 1**
PREPARATORY READING BOOK
PARTICLES AND RADIATION
3.2.2: ELECTROMAGNETIC RADIATION

Volume **Two**

NAME	
PHYSICS CLASS	
MODULE TEACHER	
ALPS GRADE	



A-LEVEL PHYSICS

TOPIC 2

READING 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 booklet, along with the student workbook, must be brought to all Physics lessons with the appropriate teacher.

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

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

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	$E = hf = \phi + \frac{1}{2} mv^2_{max}$
Threshold Frequency	$f_0 = \phi/h$ 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 these definitions.

VIDEO

COURSE OVERVIEW

To watch a video looking at all of the concepts in electric fields, please scan one of the following codes with your smartphone.

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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.	

Student Checklist

Have I…….	**Yes or No?**
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	

NOTES

Key Topic Warning
This topic is very common for questions on previous A-Level Papers.

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.

Here are the main conclusions of the photoelectric effect

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 a maximum value. This maximum value increases with the frequency of radiation.

Conclusion 3

The intensity of radiation is the amount of energy per second hitting an area of the metal. The maximum kinetic energy of the photoelectrons is unaffected by varying the intensity of the radiation.

Conclusion 4

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

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

Study Tip

This equation is found in the data booklet.

Learn the key terms of each part of the equation.

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).

Tip

In this equation, kinetic energy and energy of a photon must be in Joules.

Remember 1eV = 1.60 X 10^{-19}J

He represented this with the equation:

Study Tip

This equation is found in the data booklet.

Learn the key terms of each part of the equation.

$$hf = \phi + E_K$$

Remember these free electrons can move in a current.

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

Study Tip

Photoelectrons are just the electrons released from a metal's surface.

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.

Study 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.

Study Tip

This equation is **not** found in the data booklet.

This must be derived from other equations.

$hf_0 = \phi$ 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.

Examination Tip

It is a common question to ask why there is a current only if the frequency of the electromagnetic radiation hitting a surface is above a certain value.

energy of photon (1 mark)

is greater than the work function (1 mark)

so, electrons are emitted (1 mark)

Examination Tip

It is a common question to state and explain the effect on the current when the intensity of the electromagnetic radiation is increased.

increased intensity means more photons incident per second (1 mark)

current greater OR more electrons emitted per second (1 mark)

Examination Tip

It is a common question to ask what would happen if electromagnetic radiation was shined on a positively charged plate.

The process involves the ejection of electrons which are negatively charged. (1 mark)

Any electrons ejected will only make the positive charge greater. (1 mark)

Examination Tip

It is a common question to ask why the kinetic energy calculated is a maximum value.

The work function is the minimum amount of energy needed to remove the electron from the zinc surface (1 mark).

Examination Tip

It is a common question to describe the photoelectric effect.

Photons of light incident on the metal surface cause the emission of electrons (1 mark)

The electrons emitted are those near the surface of the metal (1 mark)

Examination Tip

It is a common question to describe how light can demonstrate wave properties (as well as particle properties)

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

or

interference patterns (light and dark fringes) using two slits or diffraction grating (1 mark)

Only waves diffract and interfere (1 mark)

Examination Tip

It is a common question to define work function.

the minimum energy required by an electron (1 mark)

to escape from a (metal)surface (1 mark)

Study Tip

The key thing about the photoelectric effect is that is shows that light can not just act as a wave. Certain observations of the photoelectric effect can not be explained by the classical wave theory.

Study Tip

Visible light cannot be used to demonstrate the photoelectric effect as the visible light does not have a high enough frequency to overcome the work function.

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.

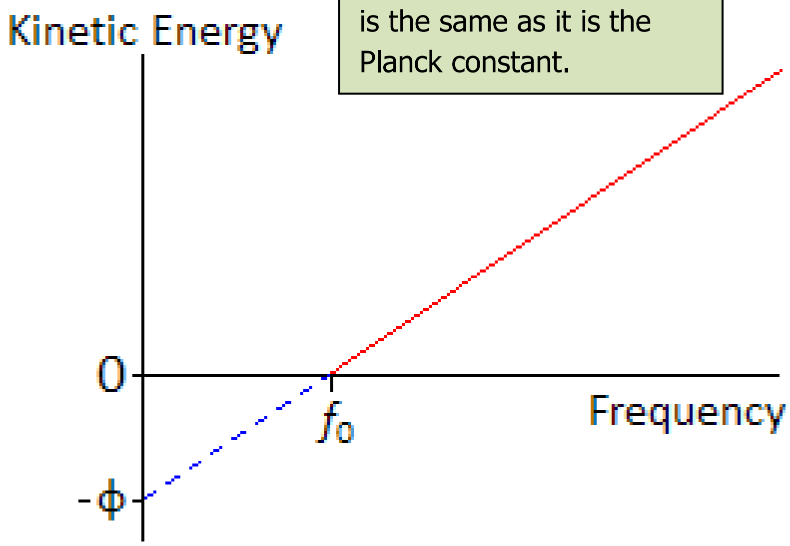
This makes the equation become: $E_K = hf - \phi$

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.

The gradient for all metals is the same as it is the Planck constant.



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.

Stopping Potential

When the electrons have become free, they will produce a current.

To stop the current from being produced (and stop the electrons from moving) a potential difference needs to be produced.
This potential difference needs to be of the same charge as the electrons (negative) – this will repel the electrons and prevent them from moving.
The potential difference needed to stop the electrons from moving is called the **STOPPING POTENTIAL.**
The stopping potential turns the kinetic energy store of the electrons into an electrical potential store.
As a result, the stopping potential is the work done when the kinetic energy turns into the electrical potential energy.

Kinetic Energy of Electron (J) = Charge of the Electron (C) x Stopping Potential (V)

The kinetic energy is the kinetic energy of one electron – this means the stopping potential is the potential difference needed to stop one electron.

This gives a low value for the stopping potential.

Study Tip

This equation is found in the data booklet.

Learn the key terms of each part of the equation.

This equation is found in the Electric Fields section of the book.

The charge of one electron is 1.60×10^{-19}C

As energy is a scalar term, the negative value of the electron charge can be ignored.

Examination Tip

It is a common question to ask how increasing the frequency of electromagnetic radiation would affect the stopping potential.

stopping potential would be greater (1 mark)

because the energy of the photons (of the electromagnetic radiation) would be greater (1 mark)

(hence) maximum kinetic energy of (photo)electrons would be greater (1 mark)

Study Tip

Asking you to explain why there is a threshold frequency and how this shows light acts as a particle is an examination favourite.

Study Tip

Remember that work done is equal to p.d. multiplied by charge.

VIDEO

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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.	

Student Checklist

Have I…….	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	

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.

Learn the joule and electronvolt conversion equations for examinations.

1eV = 1.6 x 10^{-19}J

1J = 6.25 x 10^{18}eV

eV → J multiply by *e*

J → eV divide by *e*

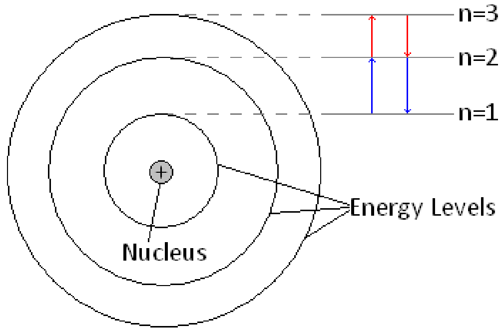
The Problem with Atoms

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.

Prior Knowledge Link
This is a topic found in a previous GCSE module **- Radioactivity**

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.
The most common way to do this is via electron collision.
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.

Study Tip

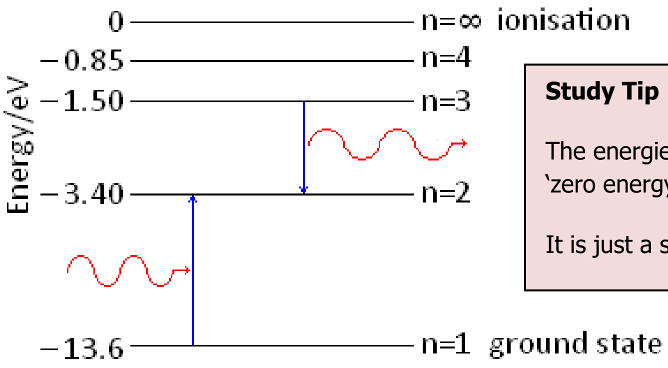
This equation is found in the data booklet.

Learn the key terms of each part of the equation.

Understand the assumptions in this calculation.

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

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



Study Tip

The energies are only negative because of how 'zero energy' is defined.

It is just a silly convention.

Examination Tip

It is a common question to ask what state the electron is in when it is at the most negative level.

The electron is in the ground state (1 mark)

Examination Tip

It is a common question to ask what state the electron is in when it is at zero.

The electron is free (1 mark)

Study Tip

As all energies are negative, just subtract the magnitude of one from the other and ignore the minuses.

Study Tip

Electrons are excited whenever energy is transferred to them – this can happen when they collide with other particles or when they absorb a photon.

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.

Examination Tip

It is a common question to define ionisation.

Ionisation is the removal (or addition) of electrons from (to) an atom or molecule (1 mark)

Examination Tip

It is a common question to ask 'Two ways to excite a hydrogen atom are by collision with a free electron or by the absorption of a photon.

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

energy needed for electron to move to higher level/orbital (1 mark)

OR

for a transition/excitation/change of levels an exact amount of energy is needed (1 mark)

all the photon's energy absorbed (in 1 to 1 interaction) (1 mark)

electron can transfer part of its energy (to cause a transition/excitation)/ continues moving/ lower kinetic energy/ lower speed (1 mark).

VIDEO

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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.	

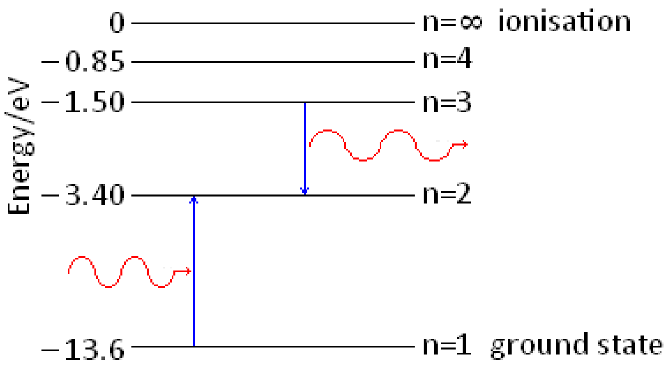
Student Checklist

Have I…….	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	

Bohr's atom

Key Topic Warning
This topic is very common for questions on previous A-Level Papers.

Niels Bohr 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'.



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.

This is due to the wave nature of electrons – they form a standing wave.

Examination Tip

It is a common question to ask why the energy levels are given in negative values.

To become free/to remove an electron (reach zero energy) energy has to be supplied (1 mark)

or

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

To move up and energy level the electron must gain the exact amount of energy to make the transition. **This is only true for excitation – not ionisation.**

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.

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

Study Tip

To work out the frequency using this equation, then the energy level difference must be given in Joules.

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

Study Tip

This equation is found in the data booklet.

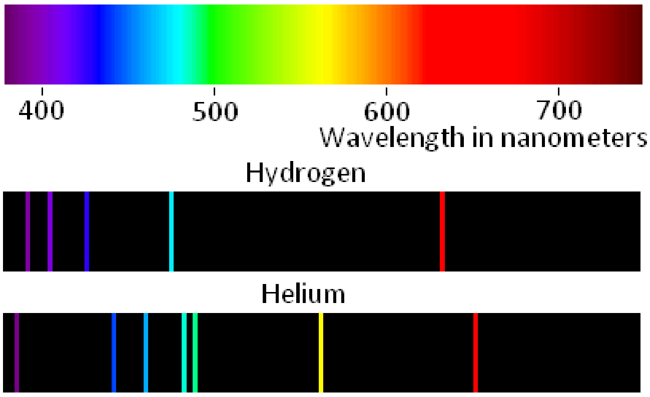
Learn the key terms of each part of the equation.

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.

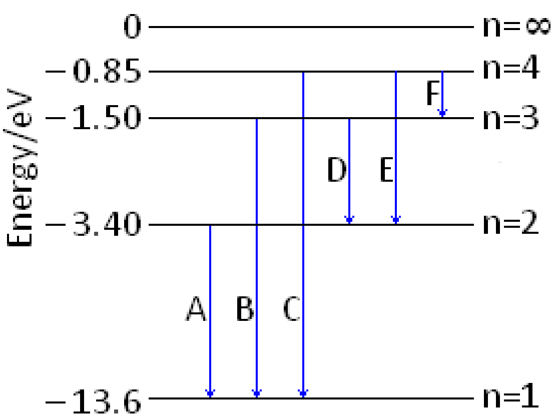
If we know the energy differences for each element we can work out which element is responsible for the light and hence deduce which elements are present.

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 3.04×10^{-19} J which corresponds to a frequency of 4.59×10^{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 spectrum unique for each element.



A large energy level difference during de-excitation leads to an ultraviolet photon is produced. A small energy level difference leads to an infra-red photon being produced.

Examination Tip

It is a common question to ask why a large potential difference is needed to produce a line spectrum.

pd accelerates electrons/produces high speed/high energy electrons in the tube (basic)

electrons have to have sufficient energy to excite the atoms/raise electrons into higher levels (advanced)

Examination Tip

It is a common question to ask what the link is between the spectrum and energy level diagram.

Visible spectrum results from excited electrons moving into the lower levels. (advanced)

Each transition results in a photon of light. (moderate)

Energy of photon is the difference in the energies of the two levels (moderate)

Frequency of light in the spectrum given by $\Delta E = hf$ (basic)

Examination Tip

It is a common question to ask how line spectra are produced with collisions.

Collisions

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

Examination Tip

It is a common question to ask how spectral lines are formed.

Formation of spectral lines

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

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

Examination Tip

It is a common question to how mercury atoms in a fluorescent tube become excited.

electrons passing through tube collide with electrons in mercury atom (1 mark)

transferring energy / atom gains energy from a collision (1 mark)

causing orbital electrons/electrons in mercury atom to move to higher energy level (1 mark)

Examination Tip

It is a common question to how excited mercury atoms in a fluorescent tube emit photons.

(each) excited electron / atom relaxes to a lower (energy) level (1 mark)

emitting a photon of energy equal to the energy difference between the levels (1 mark)

Study Tip

You might get asked to describe how a fluorescent bulb works in the examination – know it.

Study Tip

The lines are in the same place for absorption and emission spectra's because of the energy differences of the electron transitions that cause them are the same. The photons that cause each line will have the same energy, and therefore the same wavelength.

Examination Tip

It is a common question to ask how line emission spectra are formed.

Formation of spectral lines

Idea that (atomic) energy levels/states are discrete, or (emitted) photon energy is discrete (1 mark).

Idea that a photon is produced by electrons/atoms moving to lower energy levels/states (1 mark).

Idea that wavelength/frequency relates to photon energy/ΔE (1 mark).

Idea that different wavelengths/frequencies are produced (1 mark).

VIDEO

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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.	

Student Checklist

Have I…….	Yes or No?
Read through the notes of this section?	
Highlighted/underlined the key concepts of this section?	
Made my own notes based on the notes of this section?	
Brought the notes to be used in lesson?	

NOTES

Large particles have a very small de Broglie wavelength – this is why it is not observed in the macroscopic world.

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:

Study Tip

This equation is found in the data booklet.

Learn the key terms of each part of the equation.

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

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.

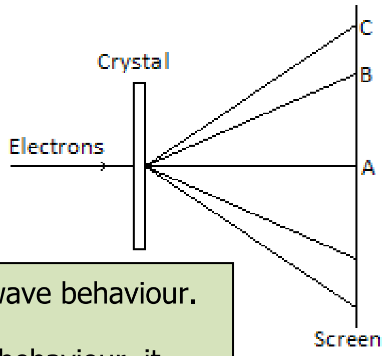
This wavelength is called the de Broglie wavelength.
The modern view is that the de Broglie wavelength is linked to the probability of finding the particle at a certain point in space. If the particle is not moving, it has no de Broglie wavelength as it has purely particle behaviour.

De Broglie wavelength is measured in metres, m

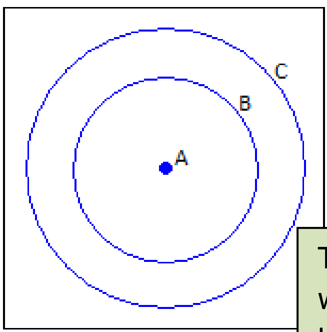
Electron Diffraction

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

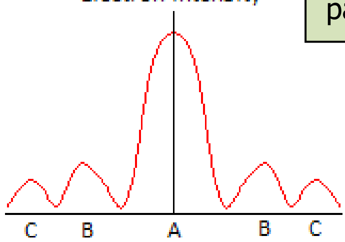
They fired electrons into a crystal structure which acted as a diffraction grating. This produced areas of electrons and no electrons on the screen behind it, just like the pattern you get when light diffracts.



Front view of Screen



Electron Intensity



Diffraction is evidence of wave behaviour.

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

The de Broglie wavelength is altered by the velocity of the particle.

Diffraction is observed for a particle, if the particle's de Broglie wavelength is similar in magnitude to the gap the particle attempts to move through.

Examination Tip

It is a common question to ask what observation deduces electron wave behaviour.

Electrons produce dark rings in diffraction experiments

Examination Tip

It is a common question to ask whether electron diffraction patterns would be observed.

You must determine the de Broglie wavelength of the electrons (this can change with velocity).

If the de Broglie wavelength is similar to the gaps of the material which the electrons pass through, then the diffraction pattern would be observed.

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:

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

Study Tip

This equation is **not** found in the data booklet.

It must be derived from other equations found in the equation booklet.

Study Tip

Make sure you know the two examples that show light acting as a wave and as a particle.

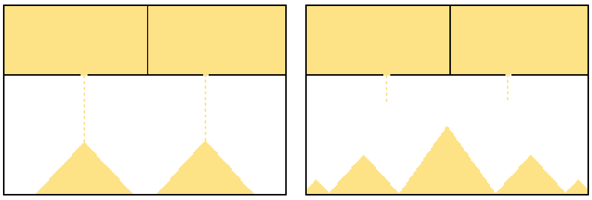
Study Tip

Electrons can be used to investigate the spacing between atoms in a crystal – an electron beam will diffract when the de Broglie wavelength of the electrons is roughly the same size as the spaces between the atoms.

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 .

Examination Tip

It is a common examination question to compare and contrast wave and particle behaviour for light and for particles.

Examination Tip

It is a common question to ask, 'how does an electron diffraction pattern supports the idea that the electron beam is behaving as a wave rather than as a stream of particles.'

Particle behaviour would only produce a patch/circle of light /small spot of light or Particles would scatter randomly (1 mark)

Wave property shown by diffraction/ interference (1 mark)

Graphite causes (electron)waves/beam to spread out /electrons to travel in particular directions (1 mark)

Bright rings/maximum intensity occurs where waves interfere constructively/ are in phase (1 mark)

Examination Tip

It is a common question to 'explain how the emission of light from the fluorescent screen shows that the electrons incident on it are behaving as particles.'

Electrons must provide enough (kinetic) energy

'instantly' to cause the excitation

OR

the atom or energy transfer in 1 to 1 interaction

OR

Electron can provide the energy in discrete amounts

OR

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

Any 2 from

Idea of light emission due to excitation and de-excitation of electrons/atoms (1 mark)

Idea of collisions by incident electrons moving electrons in atoms between energy levels/shells/orbits (1 mark)

Light/photon emitted when atoms de-excite or electrons move to lower energy levels (1 mark)

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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 $W = F s \cos\theta$

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

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

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

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	$I = \frac{\Delta Q}{\Delta t}$ $V = \frac{W}{Q}$ $R = \frac{V}{I}$
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 $I_{rms} = \frac{I_0}{\sqrt{2}}$ $V_{rms} = \frac{V_0}{\sqrt{2}}$

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 $M = \frac{f_o}{f_e}$

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

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

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 $V_{\text{out}} = A_{\text{OL}}(V_+ - V_-)$

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

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

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

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

Bandwidth requirement:

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

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

Acknowledgements

This document has been produced by Mr J Turnbull.

All relevant information has been credited in the document.

This 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.