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AS and A LEVEL

Delivery Guide

PHYSICS A

H156/H556
For first teaching in 2015

Quantum and Photoelectric Effects

Version 2

AS and A LEVEL
PHYSICS A

Delivery guides are designed to represent a body of knowledge about teaching a particular topic and contain:

- Content: A clear outline of the content covered by the delivery guide;
- Thinking Conceptually: Expert guidance on the key concepts involved, common difficulties students may have, approaches to teaching that can help students understand these concepts and how this topic links conceptually to other areas of the subject;
- Thinking Contextually: A range of suggested teaching activities using a variety of themes so that different activities can be selected which best suit particular classes, learning styles or teaching approaches.

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Section 4.5

This section provides knowledge and understanding of photons, the photoelectric effect, de Broglie waves and wave–particle duality.

In the photoelectric effect experiment, electromagnetic waves are used to eject surface electrons from metals. The electrons are ejected instantaneously and their energy is independent of the intensity of the radiation. The wave model is unable to explain the interaction of these waves with matter. This single experiment led to the development of the photon model and was the cornerstone of quantum physics. Students have the opportunity to carry out internet research into how the ideas of quantum physics developed (HSW1, 2, 7) and how the scientific community validates the integrity of new knowledge before its acceptance (HSW11).

Extension activities could include shining a UV lamp onto a zinc plate sitting on a Coulombmeter (see later section) or researching how the CCD in a digital camera works.

The following three sections are arguably the most engaging of the A Level, particularly for the students; not because they are filled with engaging experiments or great moments of group work, but because they introduce and explore the development of quantum physics. This development was at a time when it was felt by some that physics had reached the pinnacle of what it could achieve; with the introduction of Maxwell's work to explain, essentially, the whole of electric, magnetic and electromagnetic phenomena, physics had done its job, and it seemed there was nothing else to do. Then along came shining ultraviolet light onto zinc and it all changed!

This section of work considers the *particle* side of wave-particle duality. It contains information that is developed through the lessons, on:

- The nature of light in that it shows wave-particle duality
- The properties of photons in that they are lumps of electromagnetic energy
- Introduction to the electron-volt as a unit of convenience for energy
- Planck's constant (*h*) – a crucially important constant which effectively determines the strength of quantum effects in the universe.

Students should be able to demonstrate and apply their knowledge and understanding of:

4.5.1 Photons

(a) the particulate nature (photon model) of electromagnetic radiation

(b) the photon as a quantum of energy of electromagnetic radiation

(c) energy of a photon; $E = hf$ and $E = \frac{hc}{\lambda}$

(d) the electronvolt (eV) as a unit of energy

(e) (i) using LEDs and the equation $eV = \frac{hc}{\lambda}$ to estimate the value of Planck's constant *h*

(ii) determining Planck's constant using different coloured LEDs.

4.5.2 The photoelectric effect

(a) (i) the photoelectric effect, including a simple experiment to demonstrate this effect

(ii) demonstration of the photoelectric effect using e.g. gold-leaf electroscope and zinc plate

(b) a one-to-one interaction between a photon and a surface electron

(c) Einstein's photoelectric equation:

$hf = \varphi + KE_{max}$

(d) work function; threshold frequency

(e) the idea that the maximum kinetic energy of the photoelectrons is independent of the intensity of the incident radiation

(f) the idea that rate of emission of photoelectrons above the threshold frequency is directly proportional to the intensity of the incident radiation.

Taken within the historical context of a subject that was felt by many to have achieved all that it could, the photoelectric effect took physics into a new realm of understanding the universe – one based largely on probabilities rather than certainties.

The photoelectric effect was a crucial experiment in physics because it showed, beautifully, how the wave model and the (soon to be developed) particle model were in conflict.

As with many quantum phenomena, the basic process in the photoelectric effect was easily explained using the waves model, but this section of work focuses on the depth of the data, the fine experimental details of the investigation. This is where the wave model met problems and led to the development of Einstein's particle model for light.

Beyond all the wonderful aspects of this work, it is a good example of why physicists focus on the fine detail – because that is where the devil is!

Curriculum content

4.5.3 Wave-particle duality

(a) electron diffraction, including experimental evidence of this effect

(b) diffraction of electrons travelling through a thin slice of polycrystalline graphite by the atoms of graphite and the spacing between the atoms

(c) the de Broglie equation $\lambda = \frac{h}{p}$.

This section considers the conclusions of the previous work to discuss the wave and particle nature of electromagnetic radiation. It is effectively quite short in that it summarises the problems we have with describing everything that light does – sometimes it behaves as a collection of waves and sometimes as a collection of particles. After looking at the experimental evidence supporting both models, it concludes that both are correct ... and incorrect! Both models are needed, hence *wave-particle duality*.

The section then moves on to consider matter waves, with (de Broglie coming to) the same conclusion – matter also shows wave-particle duality. Electron diffraction is given as one of the important pieces of experimental evidence of this effect.

Approaches to teaching the content

This part of the course looks at one of the most intriguing aspects of particle physics – "wave-particle duality". One way of approaching this section of work is through historical development:

1) The history of the theory of light.

   Water (surface) waves (i.e. ripples) show the following (wave) effects: Reflection, Refraction, Interference, Diffraction – and they can all be explained as the ripples being a wave. The 'wave' is also easy to see on the surface of water. Light also shows these effects and therefore by extension, light was a wave (although at the time, the nature of the wave was unknown).

   Maxwell pulled together a huge amount of apparently disparate information on electric, magnetic and electromagnetic effects into one *simplifying* theory and explained it all.

   Therefore, light was definitely a wave!

2) The photoelectric effect.

   In 1887/88, Hertz shone ultraviolet light onto a plate of zinc and produced sparks. The experiment was repeated, shown to be valid and explained using the wave model:

   - Waves contain energy and *interact* with the electrons in the zinc atoms which in turn gain energy from the wave and use this to escape from the nucleus
   - A greater intensity of light produces more photoelectrons.

3) Problems with the wave model and photoelectricity.

   The wave model could NOT explain the following experimental details for the photoelectric effect:

   - Below a certain *cut-off* or *threshold frequency*, no electrons were emitted from the metal, regardless of the intensity
   - For a given electromagnetic frequency, the maximum kinetic energy of the photoelectrons is a fixed value, unaffected by the intensity of the light
   - Regardless of light intensity, the time delay in shining light and producing electrons is virtually zero.

   Students need to be aware of both the successes and failures of the wave model when trying to explain the photoelectric effect.

4) Einstein's particle model for light.

   Einstein assumed that light of frequency *f* contains packets, or quanta, of energy *hf*. On this basis, light consists of particles – *photons*. The number of photons per unit area (of cross-section of the beam of light) per unit time is proportional to its intensity. But the energy of a photon is proportional to its frequency and is independent of the light intensity.

   The minimum amount of work or energy necessary to take a free electron out of a metal against the attractive forces of the surrounding positive ions is called the *work function* of the metal, φ.

   Extension work – Note that the work function is related to thermionic emission since this phenomenon is also concerned with electrons breaking away from the metal.

   Einstein's quantum model considers the photoelectric effect as the interaction of a particular electron with a particular photon – a *one-on-one* process. Incident photons are absorbed by electrons and the energy is used to eject them. If the energy of a photon is not high enough, the electron cannot escape - this explains both the threshold frequency and the (almost) instant emission of electrons.

   A further discussion of the details of the model based on conservation of energy produces the photoelectric formula and allows a discussion of how the maximum kinetic energy varies with incident frequency and how it can experimentally be measured.

5) Wave-Particle Duality.

   So what is light, a collection of waves or particles? The answer is both and neither. Light seems to behave as one or the other (never both!), depending on the situation:

   - When the energy *propagates*: the wave model MUST be used
   - When the energy *interacts*: the particle model MUST be used.

6) Matter Waves.

   de Broglie suggested that matter (i.e. stuff with *mass*) also showed WP Duality. This was an amazing unifying idea in physics: i.e. everything is somehow the same – light and matter are both things that can sometimes be considered as a collection of waves and sometimes as a collection of particles.

   - The wavelength of matter is given by $\lambda = \frac{h}{p}$
   - The square of the wave shape is proportional to the probability of finding the object, i.e. the wave for matter is a *probability* wave.

7) Why do we need WP Duality?

We do not know what light and matter actually are – WP Duality is a reflection of our ignorance of what these things actually are so we are left with two models.

8) Quantisation.

Students should already be aware of the fact that some quantities are quantised i.e. come in *lumps*. For example charge is a quantised quantity – it comes in lumps of 1.6×10^{-19} C (revised when quarks are considered).

Like charge, energy is quantised in lumps with the difference being that the size of the lumps of energy depends on the system properties (mass of the object, physical size, etc).

This allows quantum physics to explain the atom and electronic bonding, i.e. quantum physics explains the whole of chemistry!

Common misconceptions or difficulties students may have

The points given below are some of the typical problems students have with this topic area.

In each case, the problem is stated and then briefly discussed.

Each one could be the basis of a class discussion, a piece of homework research and a class assessment. In the latter, it is suggested that:

- A statement/question/problem is presented to the class.
- Every student is given 5 minutes to write down their thoughts and answer to the work
- The next 10–15 minutes are used to allow students to read what they have written to the class and these thoughts and comments are discussed as a class
- Finally, the students are given another 5 minutes to write down a new answer to the problem, based on the discussion.

The above process allows the students to realise that their first thoughts are rarely their best. Discussion and the use of additional sources of information (in this case their peers) is a good method of considering problems. They MUST think before they put pen to paper to explain something.

1) Wave-Particle Duality cannot be correct!

One of the main problems for students considering this topic area is that WP Duality is counter-intuitive. It seems wrong and rational thought surely means it cannot be correct. This idea can be explored with students and generates some fascinating discussions – see below for more suggestions.

It should be pointed out that probably the most amazing thing about WP Duality is that it works and we have no other theory that does. If we do not accept WP Duality (until someone shows us something better), then we cannot explain why atoms exist in the way they do.

2) Photoelectrons – are they the same as *normal* electrons or are they different in some way?

Not a common question for students to ask, one that, if presented to them, they are unsure about. It allows the teacher to discuss what we mean by an electron, the idea of fundamental particles and the fact that electrons are identical and indistinguishable.

3) Why can't the wave model explain reflection?

This is an interesting question because it is a really good example of what we mean when we say that the wave model does not explain the photoelectric effect. This statement does not mean that there is no argument that can be used to explain a phenomenon – the wave model can explain the photoelectric effect by simply stating that *waves have energy and the electrons use the energy to escape*. However the point of the problem is that it may be able to explain some aspects of the effect, but when the detailed experimental observations are considered, it cannot explain them all.

In this example, the problem for the student is that they simply think that reflection is the *bouncing* of the object off a barrier of some sort (like a ball off a wall). However, there are numerous simulations of waves travelling down a string with fixed and open ends, that show the phase change happening on reflection from a fixed end (the excellent PhET site has many simulations: https://phet.colorado.edu/en/simulation/wave-on-a-string and is highly recommended). The idea of *phase* has no meaning for a particle and so the particle model cannot explain the phase changes that can be seen when reflection happens – hence the particle model fails to explain reflection.

4) How does a wave interact with an electron to allow it to be emitted?

This is a good link to other areas of the syllabus and, in particular, 4.1.1 (charge), 4.4.1 (wave motion), 4.4.2 (electromagnetic waves), 6.2.2 (Coulomb's law). The idea is that the electron is charged and interacts with the electric component of the wave. This electric field creates an oscillating force on the electron which periodically gives it extra energy, until eventually it has enough energy to escape.

This description is the basis of the *time problem* for the wave model in explaining the photoelectric effect. Namely, if the light intensity were reduced to a very low level, this would be seen as the wave having a small amplitude. In this case, the oscillating electric force from the wave would be very small and it would take a long time for an electron to gain enough energy to escape – calculations can place this time delay at hours!

This question is also good because it allows teachers to reinforce the idea that students should always be questioning *why* things happen the way they do in physics – they should not just accept things, but rather rationalise where possible and try to *understand* the processes involved.

5) What does the word *interact* mean in particle physics?

This question could be answered by also linking it to sections 5.4 and 6.2 (gravitational and electric fields respectively). This allows the concept of the field to be discussed in more detail – a field being described as a *region of influence* around an object. In this case, linking back to the question in hand, the term *interact* is a reference to the fact that there is an influence somewhere, i.e. the electron interacts with the photon and is influenced by it.

This can also link to aspects of nuclear physics in discussing the physics of the *distance of closest approach* and *alpha scattering*. This is a good example of an influence that does not require physical contact, yet despite this we still discuss the idea of a collision: i.e. a collision is when a particle is influenced in some way, but does not have to actually have physical contact.

6) Why can't electrons absorb more than one photon?

This is actually a common question from students and the answer is that they can, but the probabilities are low and this secondary effect is ignored when discussing the photoelectric effect. It is all a case of probabilities, and in this case, they are very low.

7) Can electrons absorb a photon when it has already been excited into a higher energy level? See point 6!

8) What is a probability wave?

This is a big question for students because the typical way that matter waves are considered is for the teacher to discuss the diffraction of matter. This is important since the specification requires the students to be aware of electron diffraction. If the diffraction of a person is considered as they move through a doorway, the imagery for the students is often that *diffraction* literally means that the person takes on the shape of the diffraction pattern – they widen and lose their shape! This is clearly wrong and inconsistent with the strength of the electric force between the atoms in a solid. Hence, it is important to explain that the wave is a probability wave – indicating the probability of being at a certain place.

On a slightly different level, the diffraction effect on a person when they move through a doorway does raise the issue of *free will* – do you move where you want, or does physics determine where you go?

Conceptual links to other areas of the specification – useful ways to approach this topic to set students up for topics later in the course

This section of work makes use of information from a range of areas of the specification. For example:

- 2.1 Physics quantities and units
  This allows teachers to emphasise the importance of SI units but also that there exists a set of *units of convenience*, the electron-volt being one of them.
- 3.1.1 Kinematics
  The importance of conservation of energy in the discussion of the particle model of the photoelectric effect should not be played down. Einstein's mathematical description was based on it and the importance of what happens to the photon energy left after the electron is emitted is explained with kinetic energy.
- 4.1.1 Charge
  Charge is the crucial property that electrons have that allows them to be affected by electromagnetic fields. Although the wave model was ultimately not useful, an understanding of how the model worked is needed in order to understand why the *time-delay issue* was an important one.
- 4.4.1 Wave motion
  According to the wave model, the movement of an electromagnetic wave across the region where electrons were located allowed the electrons to be excited.
- 4.4.2 Electromagnetic waves
  Obviously crucial since the photoelectric effect is associated with a property of these *waves*. It is important that students are aware that the waves have a magnetic and electric component, and also how these fields allow the waves to interact with matter.
- 6.2.2 Coulomb's Law
  The attraction caused by the negative electron and the positive nucleus has to be overcome when an electron is emitted from the atom. Effectively the strength of this force within the material is indicated by the work function for the solid.
- 6.4.1 The Nuclear Atom
  The discussion of WP Duality lends itself to a derivation of the quantum energy equation for a *free* particle *confined* to a region of space. This formula shows that not only is the mass of the particle important but also the size of the confining space. As such, this can be used as a guide to explain the difference between atomic energy levels and nuclear energy levels. From this, the smaller size is shown to be the reason why nuclear energy transitions are in the gamma spectrum.

  This is an interesting way of moving from atomic to nuclear physics.

Activities

Learner Activity 1
What does WP Duality mean?
One way of starting the topic of quantum physics could be to show the YouTube video: Dr Quantum – Two Slit Experiment:

https://www.youtube.com/watch?v=Q1YqgPAtzho

The video is only around 5 minutes long and is generally quite captivating for the students. It raises all sorts of questions because it seems so bizarre.

One way of using it is to show the class the video and then refuse to answer any questions. Teach the topic and then at the end, re-show the video – hopefully most if not all of the questions can now be answered by the students.

The video could be given to watch as homework, with every student told to consider the details and email TWO questions to the teacher having watched it. At the end of the topic, these questions can then form the basis of a group discussion on how much has been learnt and understood.

Learner Activity 2

Balmer lines – see Teacher Resource 1
The use of a spectrometer and a mercury and hydrogen tube to analyse the Balmer lines.

Learner Activity 3

Assessing Planck's constant with an LED array – see Teacher Resource 2
Experiment using LEDs to get a value for the Plank constant.

Learner Activity 4

Photoelectric effect
An excellent simulation for the photoelectric effect is at PhET:

https://phet.colorado.edu/en/simulation/photoelectric

It would be worthwhile for students to play with the simulation and vary the parameters such as light frequency, to see the effect it has on the photoelectrons.

Teachers could give the simulation as a piece of homework before the students actually meet the photoelectric effect. This should help with their grasp of the material.

The photoelectric effect can be literally shown by placing a zinc plate on a Coulomb meter. If a negatively charged plastic rod is then rubbed and the meter charged, the negative charge will be seen on the digital screen – usually in nanoCoulombs.

A short/long UV lamp can then be used above the zinc plate. The long wavelength shows no effect on the charge reading but when the lamp is switched to short wavelength, the charge is seen to slowly leak away.

Students are not normally impressed by the effect because the loss of charge is approximately 1nC every 5 seconds. However, if they are asked to calculate the number of electrons therefore being emitted from the surface per second, it is HUGE!

Activities

The following PhET simulations are useful in giving the students a wider vision and understanding of the material covered. In each case, the students could be simply told to interact with the simulation, or a worksheet could be developed for the material.

NOTE: The PhET site has free access and there are a variety of teacher-uploaded documents and worksheets for most of the simulations.

Learner Activity 1

The photoelectric effect

PhET simulation on the photoelectric effect.

Students could be simply told to interact with the simulation, or a worksheet could be developed for the material.
https://phet.colorado.edu/en/simulation/photoelectric

Learner Activity 2

Black-body radiation

https://phet.colorado.edu/en/simulation/blackbody-spectrum

Learner Activity 3

Digital cameras and the CCD

The optically sensitive part of a digital camera is the Charge Coupled Device (CCD). This works by having an array of insulating pillars (the pixels of the image), upon which is deposited a metal that will undergo the photoelectric effect when exposed to light.

The process is:

- The CCD elements are exposed
- The photoelectric effect happens, charging each element
- This is measured as a voltage between the top of each element and its base
- The voltage is read off by the camera electronics.

By knowing the properties of the CCD, the original light intensity can be calculated by measuring the voltage.

There are numerous YouTube videos that show this effect. It would be a useful piece of homework for students to be told to produce a 5–10 minute presentation on how a CCD works. Students could work in groups of 2 or 3 and in addition to giving the presentation, a poster could be produced along with a booklet to be handed out to all members of the class – to be checked by the teacher first!

For larger classes, the groups could be given different applications of the photoelectric effect to discuss. For example:

- The CCD
- A photomultiplier tube
- The gold leaf electroscope
- Night vision goggles.

In each case, students would discuss what it is, how it works and what it is used for.

Learner Activity 4

Determining the Planck constant using LEDs

In PAG6.1 for the Practical Endorsement learners measure the minimum potential difference across a number of light-emitting diodes, which will just cause each diode to emit photons of light. They then process the data and derive a value for the Planck constant.
https://www.ocr.org.uk/qualifications/as-and-a-level/physics-a-h156-h556-from-2015/assessment/

Analysis of the Balmer Spectrum

- Spectroscopic techniques analyse the radiation given off or absorbed by a substance.
- Everything has its own unique 'spectrum', so its spectrum acts like a fingerprint.
- Detailed analysis of a spectrum can reveal much more about its source. For example: what elements it is made from, how fast it is moving and its temperature.

A spectrometer is an instrument which allows you to look at spectra and make measurements on it. In this work, you may find the following detail of the visible spectrum helpful:

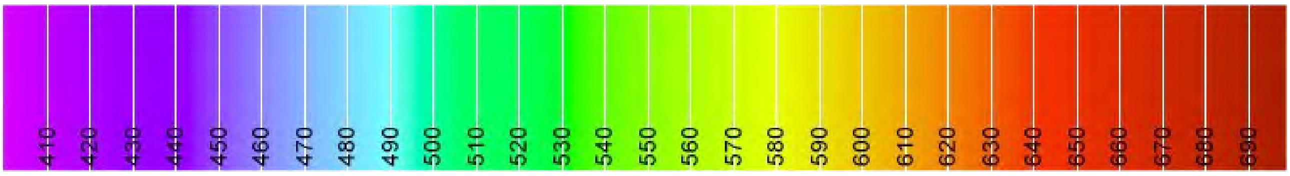


Figure 1. The visible spectrum.

Testing the spectrometer

You can become familiar with the use of the spectrometer by using it to compare the light from a mercury discharge lamp with the known values shown in Figure 2 and Table 1. Measure the angle for the different light from a mercury tube and use the information below to calibrate the spectrometer.

CAUTION (1): Do not look directly at the light from the mercury lamp as it also emits in the UV. It is safe to observe using the spectrometer, as the glass lenses absorb the UV.

CAUTION (2): All the discharge tubes use a very high voltage WHICH IS LETHAL! Do not touch the tube or its holder, or the power supply, without first switching it off and unplugging from the mains supply.

CAUTION (3): Discharge tubes are not normally made of glass – even though it looks like they are. Do NOT touch the tube with your fingers – it will cause the material to allow the gas contained within it to slowly leach out – the tube will then simply stop working for no apparent reason. Discharge tubes are very expensive to replace!

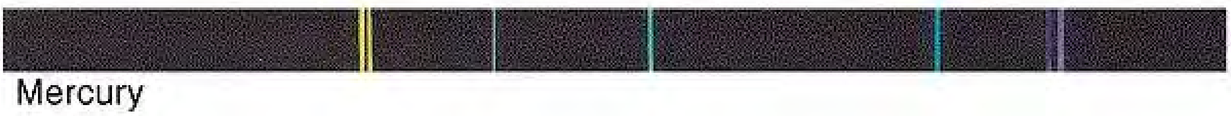


Figure 2. The emission spectrum of mercury.

COLOUR	INTENSITY	WAVELENGTH (nm)
purple	medium	404.7
purple	weak	407.8
blue	strong	435.8
green	weak	491.6
green	strong	546.1
yellow	strong	577.0
yellow	strong	579.1

Table 1. The visible lines for mercury.

Measurement of the Balmer Series

The Spectrum for hydrogen is shown in Figure 3.

Figure 3. The (Balmer) emission spectrum of hydrogen.

Set up the spectrometer with a Balmer tube and draw up a suitable data table for the spectral lines. This should include all the raw data i.e. the colour and diffraction angles of the lines. There should be four main lines in the visible spectrum, but the shortest wavelength line is quite weak and hard to see. For some people it is beyond the visible response of their eyes. However, three lines should be clearly visible.

Analysing the Balmer Series

Balmer discovered a formula for the frequencies (*f*) of the visible hydrogen lines. Later, Rydberg generalised Balmer's formula to include similar series of frequencies of lines in other parts of the electromagnetic spectrum emitted by hydrogen (e.g. the Lyman series in the ultra violet and the Paschen series in the infra red and so on). Except for the Balmer Series, each series is named after the scientist who discovered it experimentally.

Rydberg's general formula is:

$$f = R\,c\left[\frac{1}{n_f^2} - \frac{1}{n_i^2}\right]$$

where:

R : Rydberg's constant = 1.0973731×10^7 m^{-1}

c : speed of light = 3×10^8 ms^{-1}

n_i : The quantum number of the initial energy level for the electron

n_f : The quantum number of the final energy level for the electron.

Data check

Compare your experimental values with the data book values for the frequencies of the lines in the Balmer Series:

4.57×10^{14} Hz

6.17×10^{14} Hz

6.91×10^{14} Hz

7.31×10^{14} Hz

Fitting the data

Quantum numbers can only take integer values. The lowest energy level has $n = 1$, the next highest has $n = 2$ and so on.

- Why must quantum numbers be integer?
- Why is $n = 0$ not allowed?

The series of spectral lines correspond to electrons making transitions from higher energy levels to the same lower energy level with a particular value of n_f. Thus once n_f is known, the values of n_i are given by $(n_f + 1)$, $(n_f + 2)$ i.e.

Quantum Number of final level	Quantum Numbers of initial levels
1	2, 3, 4, 5, ….
2	3, 4, 5, 6, ….
3	4, 5, 6, 7, ….
etc	etc

Thus the frequencies of the lines only depend upon the value of n_i.

Multiplying out the bracket in the Rydberg Formula gives:

$$f = \frac{Rc}{n_f^2} - \frac{Rc}{n_i^2}$$

So, a graph of f (y-axis) versus $\frac{1}{n_i^2}$ (x-axis) should be linear with:

1) Slope $= -Rc$

2) Intercept $= \frac{Rc}{n_f^2}$

Combining these two results gives: Intercept $= \frac{Slope}{n_f^2}$

Remember that n_f will be a set of integer values greater than n_i.

The analysis is now to plot a set of graphs of f against $\frac{1}{n_i^2}$ assuming the value of n_f.

Only the correct choice of n_f will produce a linear graph with self-consistent values of the slope and the intercept, i.e.

1. Assume $n_f = 1$
2. Assign the values of n_i against the different values for frequency
3. Produce the graph
4. Fit the best straight line
5. Determine the slope and intercept
6. Check their self-consistency
7. Repeat this process now assuming $n_f = 2$
8. Does $n_f = 2$ give a better self-consistency than $n_f = 1$?
9. Repeat for $n_f = 3$ etc
10. Which value of n_f gives the best self-consistency?
11. For this value of n_f, calculate a value for R from both the slope and the intercept
12. Explain which determination of R is the most precise.

Niels Bohr was able to show theoretically that *R* is a combination of fundamental constants:

$$R = \frac{m_e e^4}{8\varepsilon_0^2 h^3 c}$$

So you can check the accuracy (not the same as precision, remember) of your determination of *R* with the accepted value (to 8 sf) of

$$R = 1.0973731 \times 10^7 \text{ m}^{-1}$$

Planck's Constant

An array of LEDs is provided in order to investigate the stopping potential as a function of wavelength.

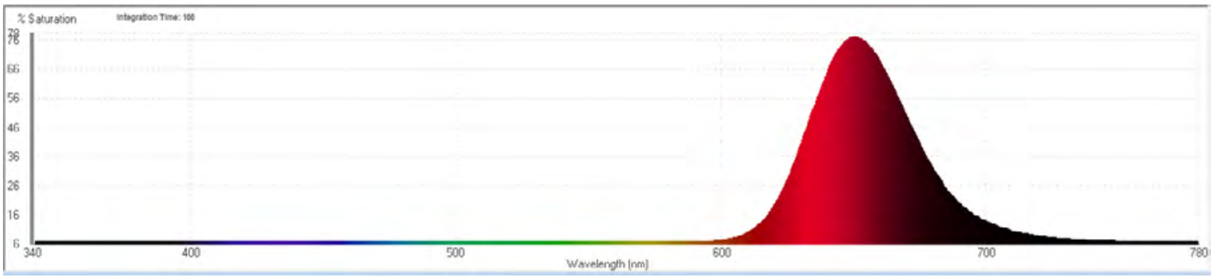
For each LED, apply a voltage, starting from zero, until the LED is **just** on. Make a note of this voltage.

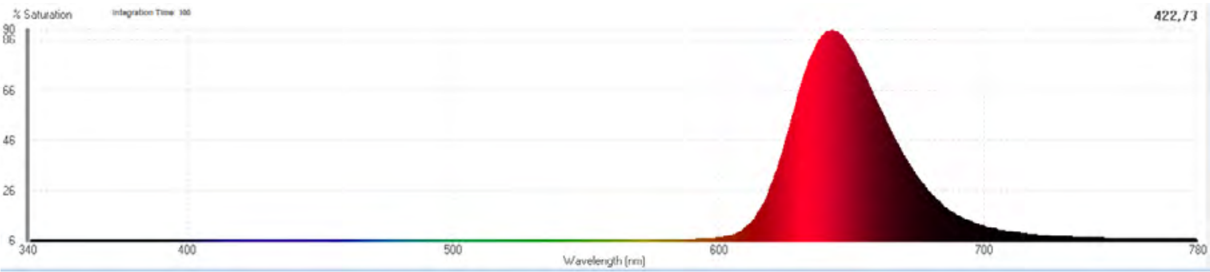
Repeat this for all the LEDs.

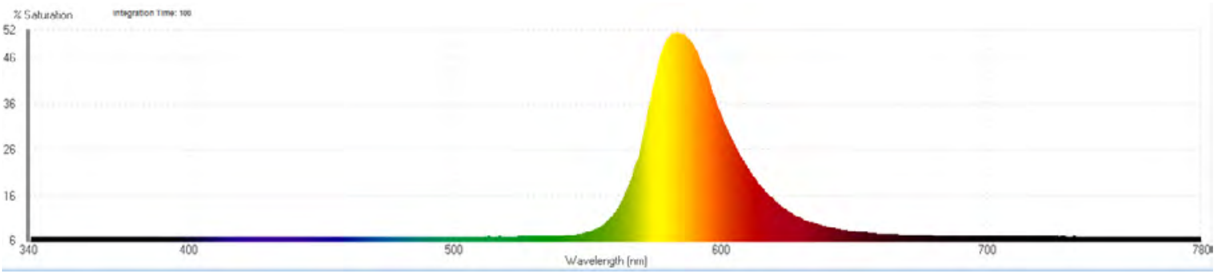
The array of LEDs will normally have the wavelength of the LED written next to it. If not, or in an extended investigation, a spectrophotometer can be used to analyse the output of each LED by turning each one on and scanning the output. Typical data is given below. It allows the student to analyse the scans and assess the central wavelength and the associated uncertainty.

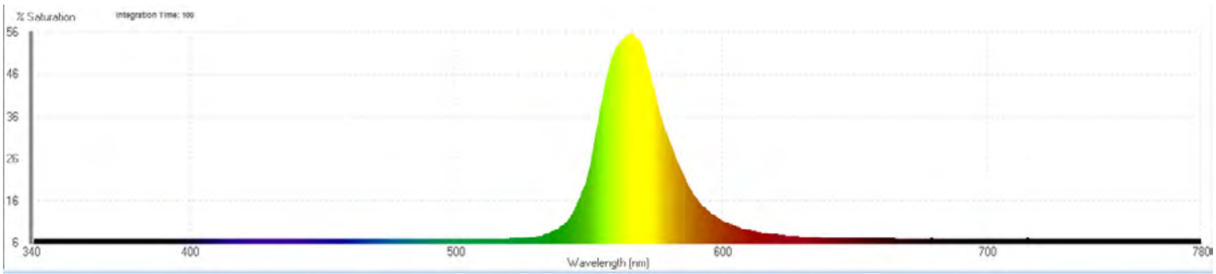
By considering Einstein's explanation of the photoelectric effect and the idea of *stopping potentials*, the students should be able to analyse the data to say something about the physics going on in this process and be able to calculate the value for Planck's constant.

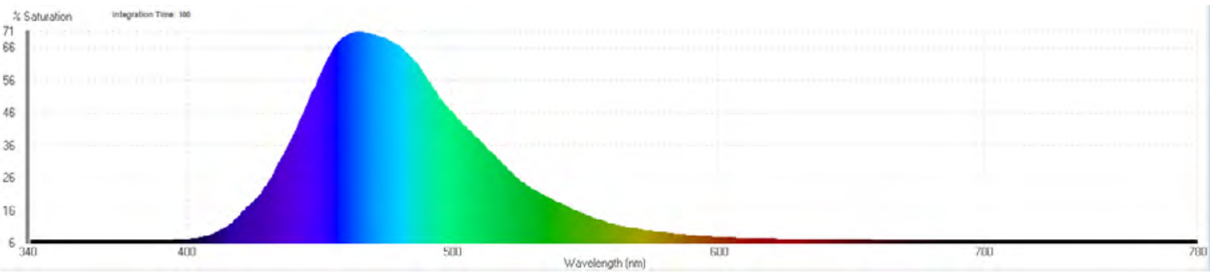
LED array – data











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