AS and A Level Physics

TOPIC GUIDE: WAVES AND THE PARTICLE NATURE OF LIGHT

PEARSON

Introduction

This guide is intended to help support teachers unfamiliar with this specification and to provide some background information on the parts of the topic that are new – both from a teacher's perspective to ensure clarity of what is expected, and from a student's perspective when discussing transition from GCSE and addressing misconceptions.

This guide can be used as a reference document for teachers, and parts of it (such as the worked examples) could work as revision material for students.

Included in this guide are:

- some ideas on how to address common misconceptions in both new and previously included content
- possible teaching sequences for key specification points where there is new or challenging content
- worked examples which teachers could use to support students in developing their problem solving skills
- links to external websites which can be used to further students' understanding.

In each section the relevant specification content is referenced using the numbered points, e.g. §60 means point 60 in the specification.

Characteristics of Waves

Wave Displacement (§59, 60, 62, 63)

Students' understanding of waves from KS4 varies considerably. The displacement of the medium is the first time students have to grapple with a function of two variables (position and time) and from a student's point of view everything to do with waves just looks like a wave (a sinusoidal graph).

Students' thinking has to be moved away from 'a picture of a wave' to a graph in which the displacement is plotted on the y-axis and one of the two variables (position or time) is plotted on the x-axis. One possible teaching sequence to achieve this is outlined in the box below.

Possible Teaching Sequence

Ask students to 'draw a wave'.

Using a rope:

- show students a transverse pulse travelling down the rope
- ask them to 'draw the wave' and compare with their original drawing
- point out that the pulse is not the familiar sinusoidal shape and that they have actually drawn a section of the rope at a particular time
- tie a ribbon to the centre of the rope and repeat the demo
- ask students to plot a graph of the position of the ribbon over time (you can use video analysis to do this with some precision or just have them watch several repeats).

Students usually perceive a distinction between drawing a graph and drawing the wave. Point out that their earlier drawing was also a graph but with 'position along rope' as the x-axis.

Show them two identical sinusoidal graphs then label the ordinate of one 'position' and the other 'time'. By relating to the demos, help them to see that the former is a photo of the medium at a fixed time (their drawing of a wave) whereas the latter is a graph of the position of the ribbon (a video analysis).

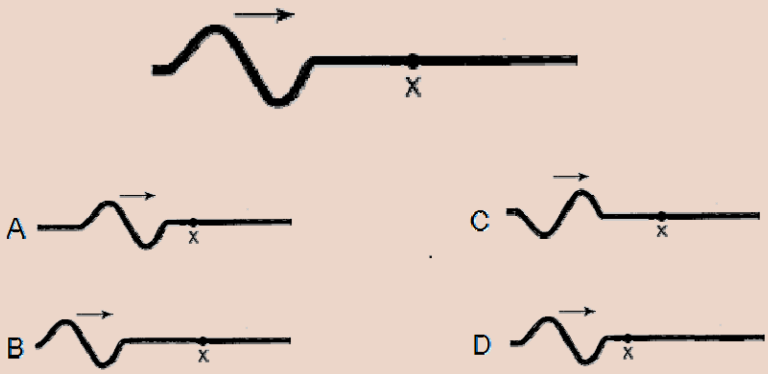
You can then re-introduce the keywords **amplitude**, **period** and **wavelength**.

This is the natural place for a discussion about frequency: students will recall it is the number of waves produced by the source in 1s and can see from the demo that this is loosely 'how fast you shake your hand'. This is useful to return to in refraction when explaining why the frequency does not change.

The graphical picture of wave motion can be used elsewhere, such as the use of sinusoidal distance–time graphs as a good starting point for SHM (specification Topic 13).

Students often also struggle with predicting the motion of parts of the medium as a wave passes. This involves connecting the variation of displacement with position with that of time: in other words, realising that the 'photo' of a wave (displacement–position graph) moves through the medium over time.

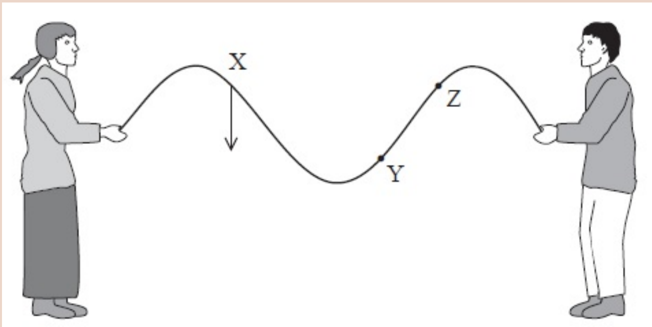
Here is a photograph of a progressive wave on a rope. The wave is moving to the right. Which picture A–D correctly shows a photograph of the rope taken a moment later? Use your answer to describe what happens to point X in the next few moments.



Several activities can reinforce the idea from GCSE that a wave transfers energy or 'a message' through the medium e.g. asking students to observe or perform a Mexican wave. Students should then see that each point of the medium will do next whatever the previous point is doing now.

Two students demonstrate standing waves to the rest of the class using a rope.

The diagram shows the appearance of the standing wave on the rope at one instant. Each part of the rope is at its maximum displacement.



Mark the position of one node on the diagram. Label this point N.

The arrow at point X shows the direction in which the point X is about to move.

Add arrows to the diagram to show the directions in which points Y and Z are about to move.

If you don't like ropes with ribbons you can also use a long trough (e.g. length of square-section gutter) and a cute pair of small rubber duckies from your local pound shop. Observing or videoing duck 1's bobbing helps students appreciate what duck 2's motion will be a short time later.

After reconnecting with GCSE waves many teachers will follow the order of the specification. However, you might like to consider:

- introducing the concept of phase by comparing the 'video' for two ribbons or the graphs of the bobbing of two ducks; how far you have to shift one graph to line up with the other is the phase difference between those two points
- introducing wavefronts and comparing to rays, ready to return to when moving from discussing refraction onto diffraction
- teaching superposition before standing waves as this is an example of superposition.

Longitudinal Waves (§61)

Students find it much harder to visualise the motion of the medium in a longitudinal wave. The above suggestions can be repeated with a slinky spring (with the ribbon tied to a central coil).

Animations can also help e.g. this one bit.ly/1wERw03 and others from the ISVR at Southampton University. In this animation it is clear that particles move forwards (to the right) when experiencing a compression and backwards a rarefaction. Why this should be so is obvious from watching the particle adjacent to the piston producing the waves (or the rightmost highlighted red dot which is in phase with the piston): as the piston moves right it compresses the medium.

- The furthest rightwards position of the particle is the point at which it is in the leftmost part of a compression.
- It then 'reverses' into the apparently oncoming rarefaction.
- Where it remains until the next oncoming compression reaches it.

In a sound wave the pressure variation is sinusoidal; high in a compression and low in a rarefaction. Somewhere in-between (on either side) the pressure is normal atmospheric. In fact the pressure variation in a sound wave is only a tiny fraction of atmospheric.

Polarisation (§82)

Students often struggle to describe polarisation in words, both the process of polarisation and the state of being polarised.

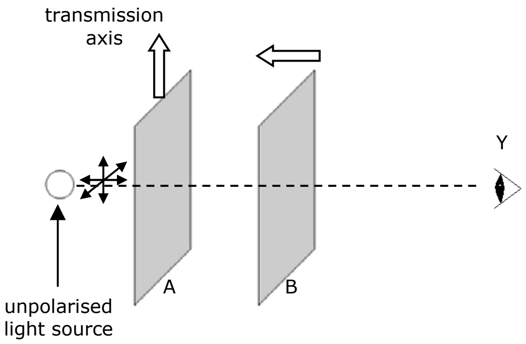
Polarisation: the process of selecting out one of the infinitely many planes of vibration perpendicular to the direction of energy transfer.

Being polarised: when the vibrations of a transverse wave perpendicular to the direction of energy transfer are confined to be in a single plane.

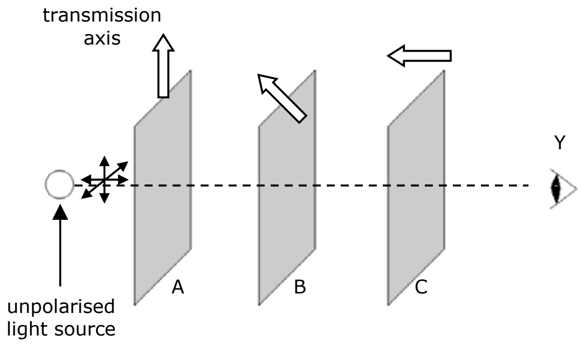
Another common area of understanding that is tested is how to detect whether or not light is polarised and the plane of any polarisation.

Pass the light through a polarising filter. Rotate the axis of the filter. If the intensity of transmitted light drops to zero then the light is polarised in a plane perpendicular to the axis of the filter. If the intensity never drops to zero the light is not polarised.

Students also often do not understand that the process is one of taking components which they will be familiar with from mechanics. The transmitted intensity is governed by Malus' law ($I = I_0\cos^2\theta$; not part of the specification) from which we see the transmitted intensity is always less than the incident intensity. Students' reasoning sometimes takes this too far and, when faced with a question based on the figure below, they assume that adding the third filter in **b** cannot increase the transmitted intensity compared to **a**.



a crossed polarising filters



b with 45° polarising filter in between

At A the light becomes polarised; at B no light is transmitted to the observer at Y because there is no component (of the electric field) along the axis of this filter ('analyser'). In **b** however, when a third filter is introduced, there is a component of the field along the axis at B but there is then also a component along the axis at C so light is again observed at Y.

Student Practice Task

Explain how you could test whether radiation from a 3 cm microwave source was polarised and determine the axis of polarisation.

Explain why sound waves cannot be polarised.

Geometrical Optics

Refraction (§71-73)

Students who studied Edexcel's GCSE Physics at higher tier will already have met §70, 72, 77, 80 whereas students with other prior learning will need more support.

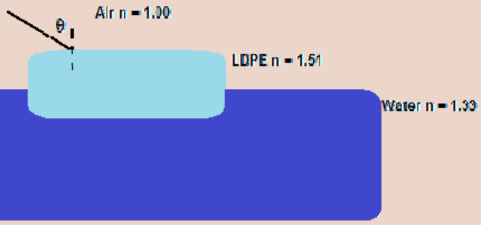
Students do not generally have difficulty with Snell's law in simple cases and one way of approaching TIR (§72-3) is from Snell's law. Give students familiar with Snell's law an example which results in TIR; ask them what 'Error' on their calculator means. Maths failure tells them that something different is happening, physically. This can then be demonstrated in the usual way, identifying the incident angle at which the change happens with the refracted angle being 90°. In this way, students can find the critical angle and decide whether TIR will take place in a given situation just using the by then familiar Snell's law.

This can be helpful to students because:

- critical angle is only $\sin^{-1}(\frac{1}{n})$ (§72) if the exterior medium has n = 1 and students often incorrectly use it when this is not the case
- they occasionally confuse C for c and get in a mess with 3×10^8 appearing as an angle
- it is instructive to see that when the maths doesn't work out it tells us some different phenomenon is happening, physically.

Worked Example

A sample of low density polythene (LDPE) floats on water as shown in the diagram. A light ray strikes the air–LDPE surface at an angle θ = 43° to the normal and enters the LDPE.



Calculate the angle between the refracted ray and the normal.

Snell's law: $n_1\sin\theta_1 = n_2\sin\theta_2$

$1.00 \times \sin 43 = 1.51 \times \sin r$

$r = \sin^{-1}(\frac{\sin 43}{1.51})$

$= 27°$ (2 s.f.)

Find the critical angle for the LDPE-water interface and hence determine whether the ray will enter the water.

Snell's law: $n_1\sin\theta_1 = n_2\sin\theta_2$

For critical angle, c, $\theta_2 = 90°$:

$1.51 \times \sin c = 1.33 \times \sin 90$

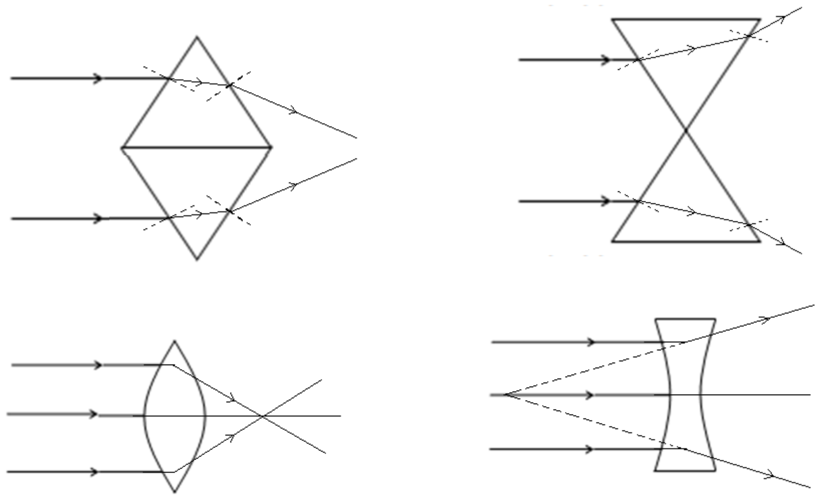
$c = \sin^{-1}(\frac{1.33}{1.51})$

$= 62°$ (2 s.f.)

The incident angle (27°) is much less than the critical angle (62°) therefore the ray **will** enter the water.

Lenses (§75–81)

Students often see lenses as somehow separate to refraction. They can be introduced to lenses as special cases of refraction by using triangular Perspex prisms as shown below where they can see the laws of refraction followed at each interface (you can find more on this in the *SupportPlus Guide* on the Edexcel GCSE Science page). This can be followed by the standard demonstration of concave and convex lenses using ray boxes with the 'triple slit'.



This is the place to point out that:

- we simplify the refraction by imagining it all happening at the centre (mid-line) of the lens (we indicate this assumption by saying they are 'thin lenses')
- rays always have arrows on them
- rays do not stop at the focus, they keep going
- the rays we have drawn are not the only rays from the object; they are just convenient ones from the infinite number what we could have chosen that help us to solve the problem at hand.

This last point is often a source of confusion for students who do not see where these particular rays have come from or assume they are some inherent property of the raybox. The lens of course works perfectly well without the triple slit in place and will still form an image with the top half covered-up, as can be demonstrated.

With these ideas understood, lens diagrams identifying the location and type of image are a matter of following the algorithm shown in the box. An example using this algorithm is available at bit.ly/1xEWMRr.

Drawing the diagram

1. Draw object.
2. Draw ray from object head through optic centre to other side.
3. Draw ray from object head parallel to optic axis up to lens.
4. Continue this ray depending on the type of lens using the diagrams above – continuing through the focus or as if coming from the opposite focus.
5. Do the rays meet?
6. Yes: draw image head here and foot on the optic axis.
7. No: continue rays backwards (dotted) until they meet; draw image as before.

Describing the image

Use three words, one from each pair.

1 Magnified or Diminished (is it bigger than the object or not)>

2 Upright or Inverted (is it the same way up as the object or not)?

3 Real or virtual? (Did you draw any dotted lines? – if yes, image is virtual.)

Real images have only real light rays passing through them (not imaginary, dotted ones) and consequently will be visible if a 'screen' (a sheet of white paper) is placed at the location of the image.

Sometimes the *value* of the magnification is also required and this can be done by scale drawing ($\frac{\text{image height}}{\text{object height}}$, and therefore a fraction if the image is diminished) or by calculation using the lens formula, $\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$.

Student Practice Task

Draw a ray diagram showing the image formed by a convex lens when the object is placed close to the lens (closer than the focal length).

Describe the nature of the image formed and determine the magnification if the object is placed 1 cm from a lens with focal length 5 cm.

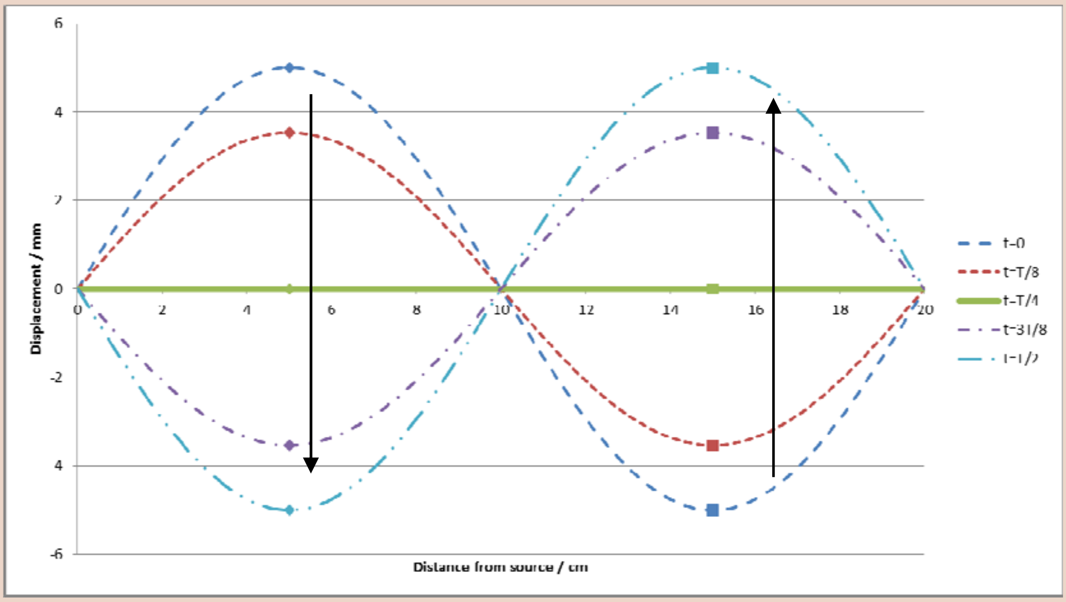
Physical Optics

Superposition (§65)

Before teaching diffraction it is necessary to have taught the idea of superposition and the other concepts in §65. Superposition can be shown using ripple tanks or animations; once students get the idea that waves just 'add up' they can ask themselves what happens if the waves are not 'in step'. Although the terms constructive and destructive interference are not used in the new specification, they are expected to be understood and are useful later in describing the diffraction grating. A useful description is to remind students of the notion of a wave as a 'message'; two waves in anti-phase give opposite messages to the particle of the medium which therefore remains stationary.

Students always seem to find coherence mysterious. When we analyse a situation involving interference to find light and dark regions, we need that pattern to remain the same over time, otherwise it would blur out and not be observable. Requiring the sources to be coherent just describes this fact; that the phase relationship we used in the analysis remains constant in time so we can actually see the pattern we deduced. This is described by saying the sources **maintain a constant phase relationship**.

Before going on to diffraction, consider teaching standing waves at this point as an example of superposition. Describing standing wave phenomena requires the same language so this is a good place to practice using it and to draw distinctions between progressive waves and standing waves. In particular it is worth emphasising the motions of particles on either side of a node.



In this graph of a standing wave, the point at 5 cm from the source (antinode, diamonds) is moving in antiphase with the point at 15 cm (antinode, squares).

Student Practice Task

The standing wave above has wavelength 20 cm. If the wave speed is 12.5 ms^{-1}, find the:

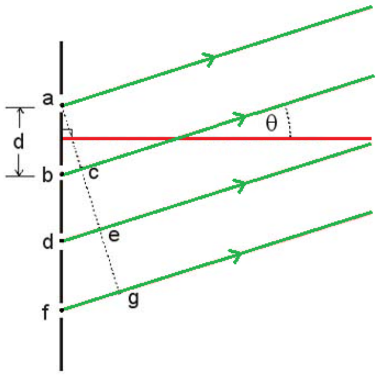
- frequency
- time period in ms
- time it takes for the point marked with a diamond to get from its maximum displacement to the equilibrium position.

Diffraction (§83–84)

Once the concept of wavefront has been taught this leads into Huygens' construction: the idea that each point on the wavefront acts a source ('of secondary wavelets'). Details can be found in any textbook and an animated explanation is available at bit.ly/1zk6k8D.

This construction is very helpful in understanding diffraction where part of the wavefront is obstructed so those obstructed secondary sources no longer contribute to subsequent wavefronts.

A **diffraction grating** comprises an obstruction with a sequence of equally-spaced narrow slits. Students can think of each slit as a single secondary source with the rest of the wavefront obstructed. It is then clear that only a small number of very specific locations (on a distant screen) will satisfy the condition for constructive interference. This is another area where animations can help e.g. bit.ly/1whhWH5. This animation links to the standard proof of the formula required for specification reference §83.



In the diagram right there will only be constructive interference at the screen if each wavelet arrives in phase and this can only happen if their path differences are whole numbers of wavelengths. So:

- *bc* has to be an integer, n, times the wavelength
- but *bc* = d$\sin\theta$ by trigonometry.

So we arrive at the condition in §83.

When using the formula in §83 students should be able to find d given the number of lines per unit distance.

Find the angle at which the first order maximum is observed when a diffraction grating with 500 lines per mm is illuminated with a laser of wavelength 720 nm.

500 lines per mm => 500000 lines per m

Line spacing, $d = \frac{1}{50\ 0000} = 2.0 \times 10^{-6}$ m

For first order, using $\frac{\lambda}{d} = d\sin\theta$ with n = 1:

$$\sin\theta = \frac{\lambda}{d}$$

$$= \frac{7.2 \times 10^{-7}}{2.0 \times 10^{-6}}$$

$$= 3.6 \times 10^{-1}$$

$$\theta = 21° \text{ (2 s.f.)}$$

Students should be aware that n cannot increase indefinitely because the rays in the diagram always go forwards through the slits (i.e. $\theta < 90°$). Experimentally they should be shown that the spacing of the spots on the wall depends on the line spacing in the grating and this affects the number of spots actually visible. They should therefore be taught to use the idea that $\sin\theta = \frac{n\lambda}{d} < 1$ and therefore $n < \frac{d}{\lambda}$.

Two common errors arise here: first, to fail to give the maximum order (n) as an integer (a result of n < 4.88 means n = 4 is the largest order visible). Second, to fail to recognise that this is the number of spots visible **on each side** of the central (zero order) spot and so the total number of **visible** spots is 2n + 1.

For the same grating illuminated as in the above question, how many bright spots would be visible on a distant screen?

$$\sin\theta < 1$$

so $n < \frac{d}{\lambda}$ for any diffraction grating

$n < \frac{2.0 \times 10^{-6}}{7.2 \times 10^{-7}}$ in this case

< 2.78

Two spots visible on each side of the central maximum therefore a total of **5 spots** are visible on the screen.

Student Practice Task

A laser of wavelength 640 nm illuminates a diffraction grating with 300 lines per mm.

Explain what is meant by the term coherent.

Find the angle of the second order bright spot produced by the grating.

Show that the maximum number of spots visible is 11.

Explain how the pattern would change if a laser producing light of higher frequency were used.

Students will find it interesting to know how diffraction gratings are used in spectroscopy; they can make their own spectrometer using a piece of old CD (see below, where this links to energy levels in atoms).

The Quantum Picture

Particles as Waves – de Broglie Waves (§86, 87, 90)

The standard way to demonstrate that 'particles' can behave like waves is to show electrons exhibiting the characteristic wave-like property of diffraction. Many schools will still have the apparatus to do this demonstration in which electrons are generated by thermionic emission and accelerated onto a graphite target producing circular diffraction 'rings'. (There is a video of this at bit.ly/1wOBofR). If you still have the tube in school there are instructions and a risk assessment for this demonstration here bit.ly/10CJ1Zs.

The development of this theory is nicely presented by Jim Al-Khalili in the first of his three-part TV series from BBC Four called *Atom* entitled 'The Clash of the Titans'. This video followed by a class discussion would be ideal coverage for specification item §90.

Waves as Particles – The Photon Model (§91–96)

The Photoelectric Effect

The key evidence supporting the idea that light can be described by a particle model is the photoelectric effect (§92, 93, 95). Many schools will be able to demonstrate this to students as described in the box below. There is an excellent interactive animation that students can use as a follow-up exploration available on the University of Colorado's PhET website (bit.ly/1rrydU5). This adds to the practical demonstration by giving students a visualisation of the effect at the particle scale.

In essence, the wave model asserts that the energy delivered by light waves depends on their amplitude (brightness). This means that, if electrons are going to be released, a bright enough light should do the job, eventually providing enough energy for electrons to absorb to become free and escape the metal surface. Since what is observed is that **no** electrons are released below the threshold frequency, no matter what the brightness or how long you wait, this is the death knell for the wave model (§95).

The energy per photon (§91) and value of the Planck constant can also be investigated experimentally with students by finding the turn-on voltage for a range of colours of LED. These are available from electronics stores like Maplin or CPC for a few pence each; keep the data sheet so you have a record of the wavelength of light they emit! There are several descriptions of the experiment on the internet such as this one bit.ly/1E6KANn.

This experiment is a great time to teach the electron–volt (§94) as it is required to find the Planck constant by this method and the energies of visible light photons work out to be a few (2–4) eV. A graph of turn-on voltage against LED frequency is a straight line with gradient $\frac{h}{e}$ (depending on the units chosen).

Warning: Be aware that the graph of voltage vs current used in the above link as a way to determine more precisely the turn-on voltage has the same shape as the 'standard' graph for the photoelectric effect (E_K vs frequency) so could be a source of confusion later.

Place a **newly-polished**, **flat** piece of zinc onto a coulombmeter (the Unilab one is common in schools).

Charge the meter with a negative charge.

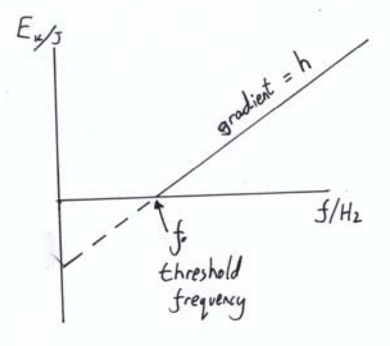
Illuminate the disk with white light, ideally varying the intensity – the charge will remain on the meter no matter how bright the light.

Illuminate the disk with a mercury vapour lamp – the meter will discharge rapidly.

For a challenge, repeat with other metals or with the meter having a positive charge and ask students to explain what they observe.

The key points to get across from the demonstration followed by study of the interactive animation are:

- each incident photon can only release one electron
- no electrons are released unless the photon energy exceeds a certain minimum value (given by hf0 where f0 is called the threshold frequency), no matter how bright the light
- this minimum depends on the metal being illuminated
- provided the threshold frequency is exceeded, the number of electrons released per second depends on the number of photons incident per second (the brightness).



This then leads to the equation in §93 which students should see as simply the conservation of energy: the photon energy is used to release the electron from the metal surface (**work function**, $\varphi = hf_0$) and any energy 'left-over' becomes KE of the electron. It is a **maximum** KE because we have not allowed for any energy losses which would reduce the energy available to the electron as KE e.g. in getting an electron to the surface, supplying energy to the metal lattice.

Arranging this equation into straight-line form and interpreting the graph as shown alongside is likely to be a common examination question.

$$hf = \phi + E_K$$
$$hf - \phi = E_K$$
$$E_K = hf - \phi$$
$$\downarrow \qquad \downarrow$$
$$y = mx + c$$

You may see elsewhere details of stopping voltage: while this experiment is not required in the specification, questions could be set on it provided enough information is given in the stem. In this experiment, the maximum KE of released electrons is determined by finding the voltage required to attract all released electrons back to the metal plate and therefore reducing the current to zero: if this voltage is V_0 then eV_0 is the maximum KE of released electrons. This is shown clearly in the PhET animation referred to above.

Student Practice Task

What is meant by the term **work function**?

Why is the kinetic energy term in the photoelectric equation a **maximum** value?

Electrons and light can each show both wave and particle properties.

- Describe briefly, without experimental details, how you would show that electrons have wave-like properties.
- Describe an experiment to determine Planck's constant using the principles of the photoelectric effect. Your answer should include the equipment you would use, the measurements you would make and a description of how you would process the data.

Line Spectra

Line spectra have been known since at least 1821 and in the late 19th century it was known that the lines in the hydrogen spectrum followed a simple pattern based on integers. Only with the development of quantum mechanics around the turn of the last century did the explanation in terms of discrete energy levels in atoms become apparent.

We define the energy of electrons which are free, far away from any atoms, as being zero. Electrons in atoms are 'bound' and require an energy input to pull them away from the nucleus. Electrons bound in atoms therefore have **negative** total energy.

Remind students that energy is just an accounting system (see bit.ly/1wK3w1h) and there is no problem with something having negative energy in the sense defined here.

Only certain values of electron energy are allowed; this can just be taken as read or students could be shown how this is similar to standing waves on a string. (A relatively simple treatment along these lines can be found in bit.ly/1DCNqru. A very advanced analysis for A level students requiring previous study of the electrostatic force can be obtained from bit.ly/1nVgmVm).

Having accepted the discrete nature of the energy levels, diagrams such as the one here can be introduced from which students should learn the following.

- The lowest level (-10eV in the example) is called the 'ground state'.
- Electrons can absorb energy from photons or collisions in a process called excitation so long as they only absorb the right amount of energy to move to another level.
- Excited electrons can return to a lower level by releasing the extra energy as a photon.
- Since there are only a limited number of energy changes possible (from one level to another) only certain frequencies of photon can be emitted resulting in a line spectrum.

Fluorescent tubes are a good example of this process, albeit with the complication of the conversion of UV photons to visible by the coating (bit.ly/1tlPZgC).

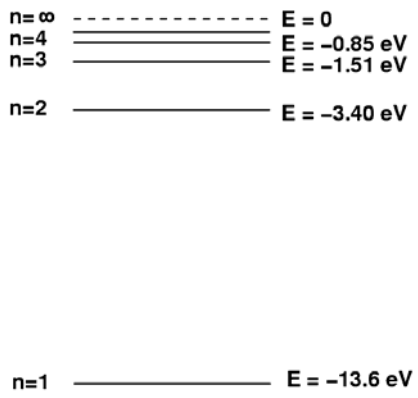
Useful summaries about line spectra can be found by following these links:

- bit.ly/1zkci9M
- bit.ly/1zkcmWM
- bit.ly/1rE5fjd

Students should be able to use E = hf to calculate the frequencies of photons emitted on de-excitation (or absorbed during excitation) and to be able to deduce all the possible transitions in a given situation as in the example below. For a challenge, students can be asked to solve this problem in the degenerate case (where more than one spacing has the same energy gap so there are more possible transitions than possible frequencies observed – the final part of the example below).

Discussing line spectra is a perfect time to re-visit diffraction gratings and perhaps have students make their own spectrometer using a piece of old CD (see bit.ly/1EHYqEn).

The diagram below shows the energy levels in a hydrogen atom.



1 What is the energy of an electron in the 'ground state' of this atom?

2 Calculate the energy in joules required to excite this electron into the n=3 level.

3 List the possible photon energies, in eV, that could be emitted as this electron de-excites.

4 Calculate the wavelength of the highest energy photon that could be emitted.

Answers

1 Ground state = lowest energy state so E = -13.6eV

2 E = -1.51 – -13.6(0) = 12.09 eV = 12.09 × 1.6 × 10^{-19} J = 1.93 × 10^{-18}J

3 3->1 12.09 eV

3->2 1.89 eV

2->1 10.2(0) eV

4 $E = hf = \frac{hc}{\lambda}$

$\lambda = \frac{hc}{E} = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{10.2 \times 1.60 \times 10^{-19}} = 1.22 \times 10^{-7}\text{m}$

Challenge

A hypothetical atom has energy levels at -10eV, -6eV, -4eV and -2eV. An electron is excited from the ground state into the state at -2eV. State the number of lines that would be observed in the spectrum due to de-excitations from this level.

- From -2eV level downwards: photons of 8, 4 and 2 eV.
- From -4eV level downwards: photons of 6 and 2 eV.
- From -6eV level downwards: photon of 4eV.
- There are 4 different energy values so 4 spectral lines.