How are light and matter similar?

Behaviour of light

- **analyse the photoelectric effect with reference to:**
  - **evidence for the particle-like nature of light**
  - **experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency**
  - **kinetic energy of emitted photoelectrons: $E_{k\,max} = hf - \varphi$, using energy units of joule and electron-volt**
  - **effects of intensity of incident irradiation on the emission of photoelectrons**
- **describe the limitation of the wave model of light in explaining experimental results related to the photoelectric effect.**

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
2, 3, 4, 9	1, 2, 3	6, 7, 8	2, 5, 6, 7	2, 3, 5, 6	5, 6, 7, 8, 9	1a, b, c, d	21a, b, c, d	20a, b	18a, b, c, d	19a, b, c, d

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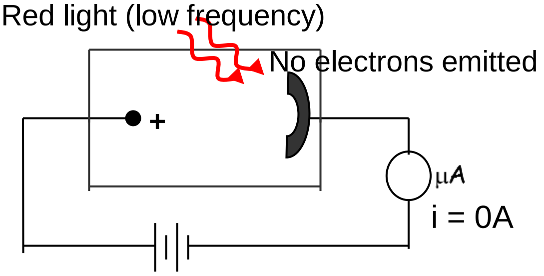
Photoelectric effect

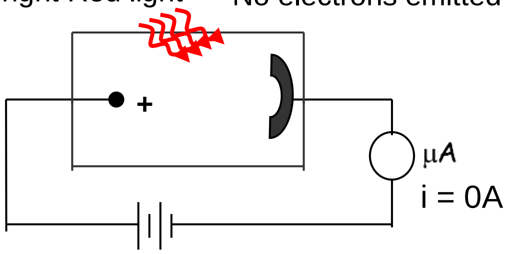
The discovery of the photoelectric effect dramatically changed the way scientists were thinking about light. The particle model had lost support since Young's double slit interference experiments. The wave model could not explain the photoelectric effect. It sometimes happens that when light falls on certain metals, electrons are ejected from the metal. These electrons are known as photoelectrons.

The experiment can be used to show that the number of electrons ejected depends upon the light intensity. As the light intensity increased, so too did the size of the current. More electrons were escaping from the metal when the light was brighter.

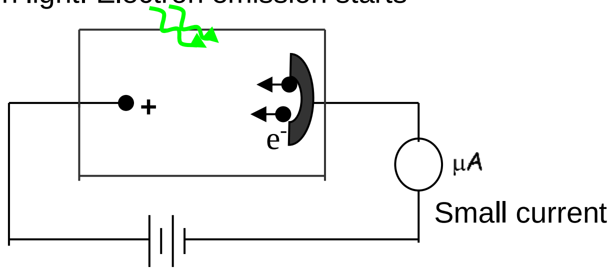
Red light (low frequency)



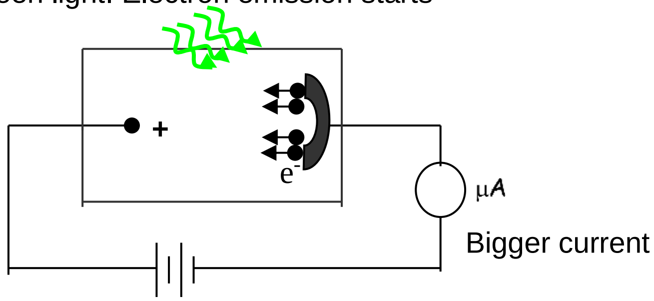
Bright Red light

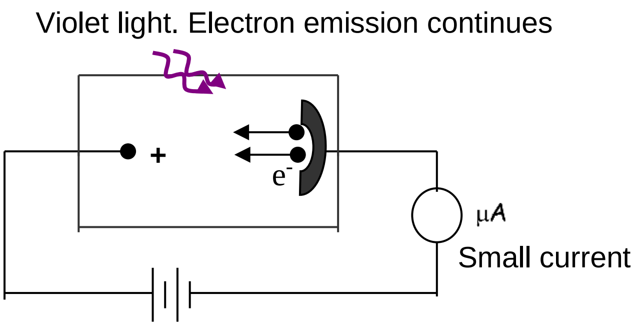


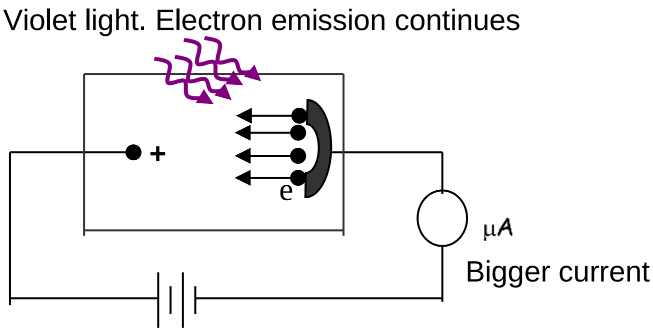
Green light. Electron emission starts



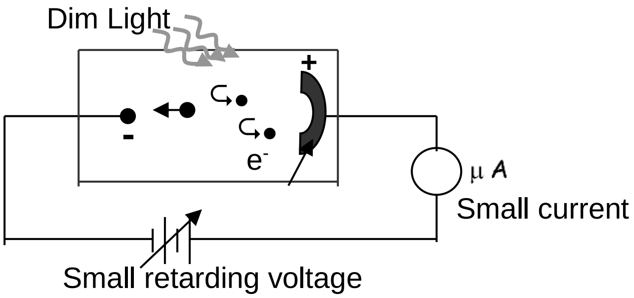
Green light. Electron emission starts

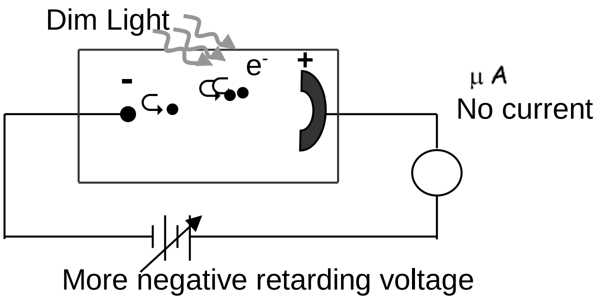






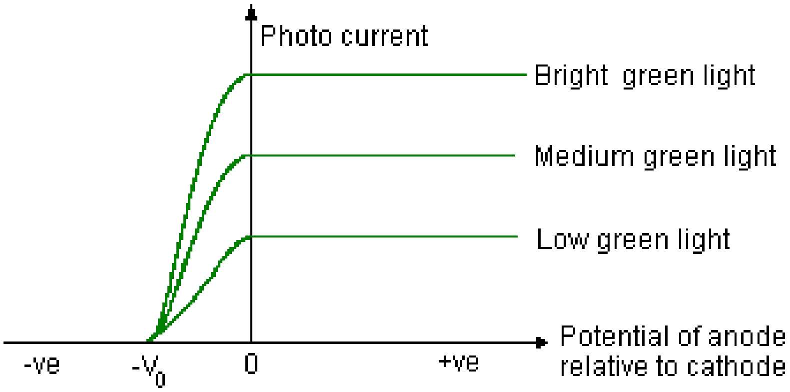
When the battery is reversed, some important results are obtained.

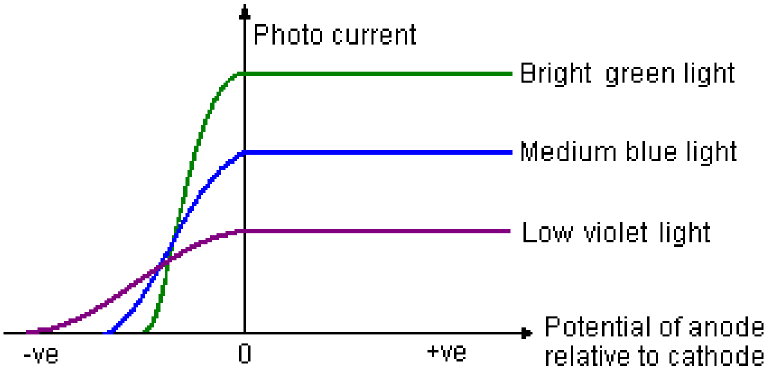




- As the anode is made more negative fewer electrons get across the tube- this means that the ejected electrons must have a range of kinetic energies. Electrons with little or no KE are stopped as soon as the anode becomes negative - those with the most KE being stopped by V_c volts. Energetic electrons come from the surface, less energetic electrons from below the metal surface.
- The value of V_c, the cut off voltage, depends upon the colour, not the intensity of the light. With most metals, low frequency light will not generate electrons.
- More intense light generates more electrons, but does not increase their energy.

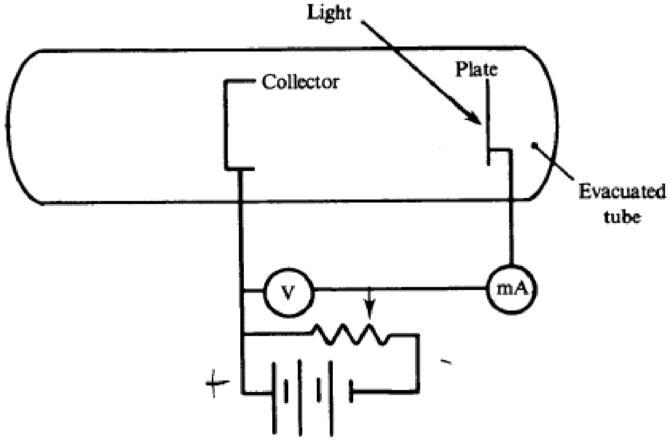
When the frequency (i.e. colour) of the light shining on the metal changes, there is a frequency at which the electrons begun to be emitted from the metal. This is called the THRESHOLD or CUT-OFF FREQUENCY (f_c). Below this frequency, no emission occurs, even for very intense light.



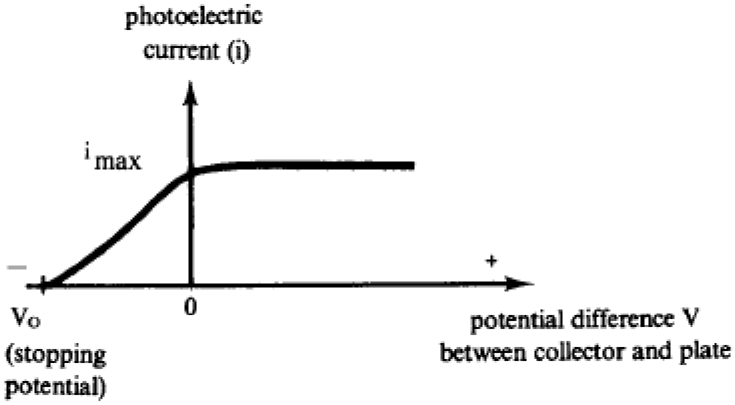


These results cannot be explained using wave mechanical ideas. These would suggest that the energy carried by the wave would be distributed among all the atoms of the metal, building up until sufficient energy was available to ionise the atoms.

Thus intense light should produce a current more quickly than dim light. This is not so, electron emission is a factor of frequency not intensity. The results can be explained if it is assumed that light comes in random packets and not waves. The energy of one of these photons is transferred to one atom only, not spread to many, and hence the photoelectrons are observed immediately.



The figure above represents a photo-electric tube, in which light of a particular frequency and constant intensity strikes the plate; electrons of charge e are emitted and travel to the collector. As the potential difference between the collector and plate is varied, the current measured by the milli-ammeter varies as shown below.



Example 5.1: 1981 Question 47 (1 mark)

Why is the photo-electric current constant at positive values of *V*?

A. The electric field between the collector and the plate remains constant as *V* is increased; thus increases in *V* do not increase the kinetic energy of the emitted electrons.

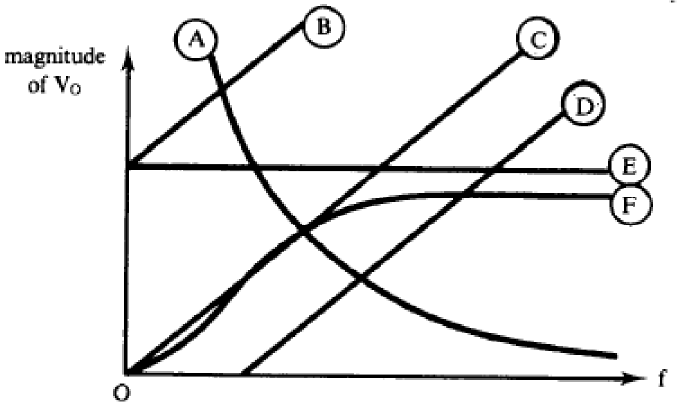
B. For a particular light intensity, there is a corresponding number of electrons emitted per second; when all of these have been collected, further increases in *V* do not increase the current.

C. All the photo-electrons have the same mass, charge, and kinetic energy, and none of these quantities is affected by changes in *V*.

D. Ohm's Law applies to the photo-electric tube; as *V* is increased, its resistance increases, and so the current remains constant.

Example 5.2: 1981 Question 48 (1 mark)

If the frequency of the light striking the plate were now varied systematically, which of the graphs **(A - F)** would best represent the relationship between the magnitude of V_o and f?



Example 5.3: 1981 Question 49 (1 mark)

In 1905, Einstein proposed the following equation to account for the photo-electric effect:

$$E = hf - w.$$

The quantity w is

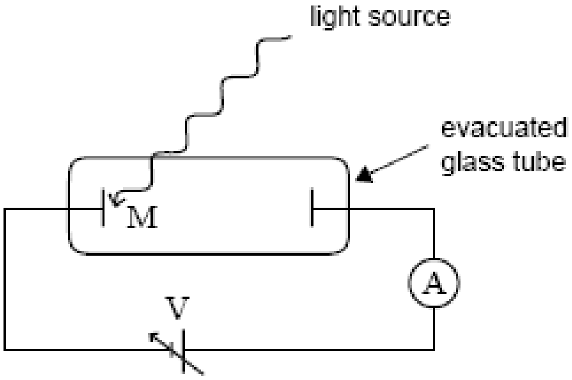
A a constant, whose value is characteristic of the particular metal used in the plate

B a constant which depends on the frequency of the light

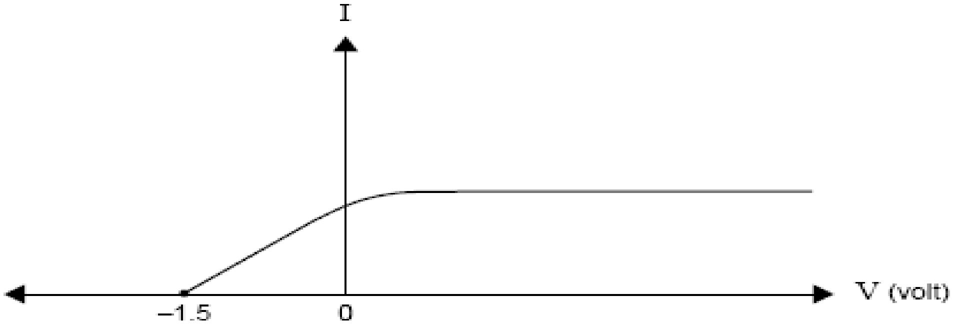
C the gradient of the i - V graph in the negative region

D equal to V_o

An experiment is carried out to investigate the photoelectric effect. Light of a single frequency shines onto a clean metal plate M inside an evacuated glass tube as shown below.



When the voltage V between the plates is varied, the current measured by the ammeter varies as shown below. V is the voltage of the right-hand plate relative to the plate receiving light.



Example 5.4: 1997 Question 2 (1 mark)

What is the maximum kinetic energy of electrons ejected from the plate M? Give your answer in joule.

The light source is replaced by one of much higher intensity.

Example 5.5: 1997 Question 3 (1 mark)

How does this affect the voltage at which the current is zero? Explain your answer using a photon model for light.

Einstein’s explanation

Einstein's explanation of the photoelectric effect was that each photon of light gave up its energy completely when it collided with an electron in a metal.

The energised electron used up some of this energy in overcoming the binding force of the atoms in the metal and escaped with the remaining energy.

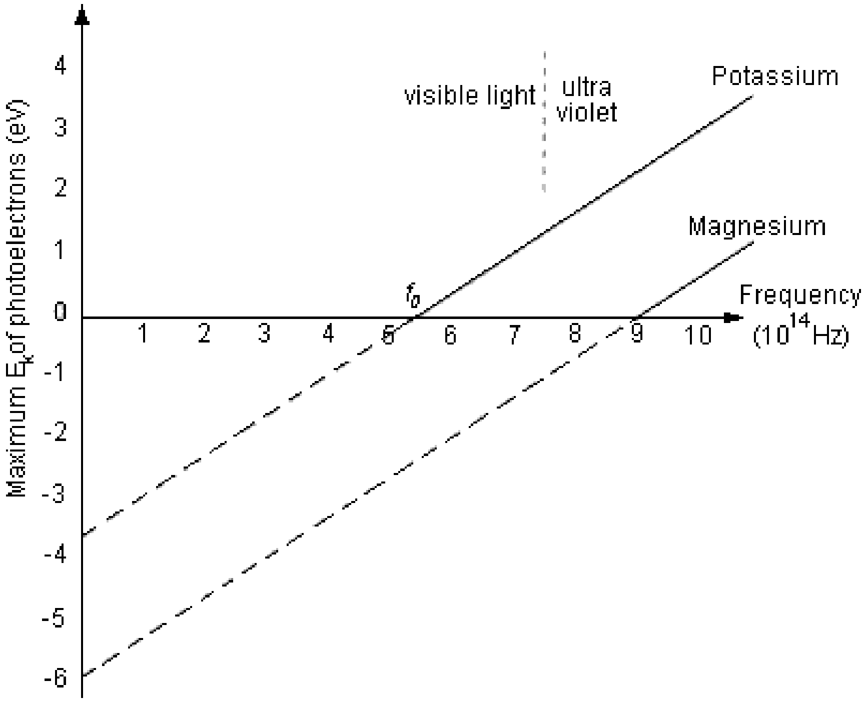
The energy that the electron uses up to escape from the metal is called the BINDING ENERGY or WORK FUNCTION (W) of the metal. Hence the work function (binding energy) is the difference between the energy of the incident photon and the maximum KE of the electrons that are ejected.

This quantity is a property of the metal and varies from metal to metal.

Thus the maximum Kinetic energy of the escaped electron is given by

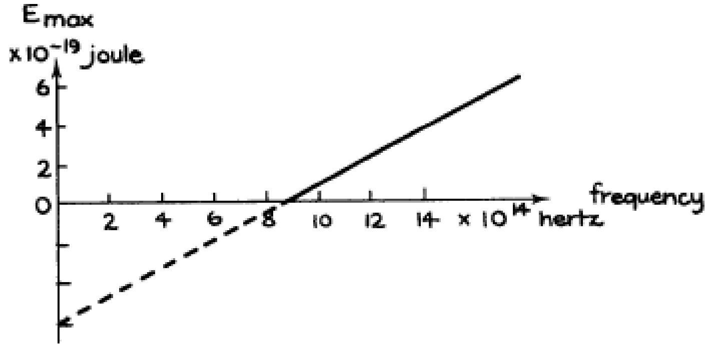
Kinetic Energy of Photoelectron: $E_K = qV_c = hf - W$

Kinetic Energy vs Frequency graph.



If a graph of the KE of the ejected electrons is plotted against the frequency of the incoming light the following can be deduced:

- There is a threshold frequency below which the electrons are not emitted.
- Different metals have different threshold frequencies
- The gradient of the graph is the same for all metals, it is Planks constant
- The equation of the graph, an energy equation, is $E_k = hf - W$ where E_k is the Kinetic Energy of the ejected electrons, h a universal constant and W a constant for the material. This can be written as $hf = E_k + W$
- The constant h is Planck's constant and has the value of 6.626×10^{-34} J s. or 4.136×10^{-15} eV s.
- W is either called the work function or the binding energy of the metal.



Monochromatic ultraviolet light is incident on a magnesium surface, from which electrons are ejected. The graph shows the maximum kinetic energy of individual electrons for light of various frequencies.

Example 5.6: 1979 Question 66 (1 mark)

The gradient, *k*, of this graph can be used to estimate

A the charge on the electron

B the charge/mass ratio of the electron

C Planck's constant

D the ionization energy of magnesium

Example 5.7: 1979 Question 67 (1 mark)

What is the minimum amount of energy, E_{min}, required to remove a single electron from a magnesium surface?

Example 5.8: 1979 Question 68 (1 mark)

If another metal had been used instead of magnesium, one would expect that

A. k and E_{min} would both have different values

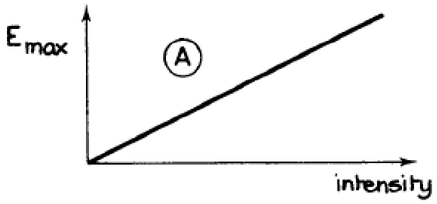
B. k would be different, but E_{min} would be the same

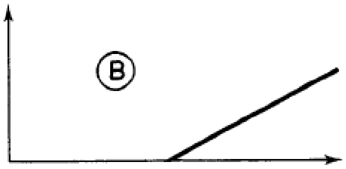
C. k would be the same, but E_{min} would be different

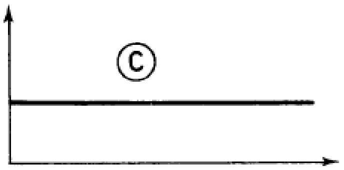
D. k and E_{min} would still be the same.

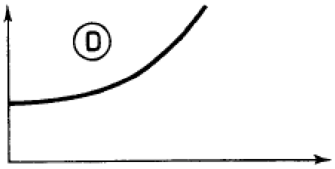
Example 5.9: 1979 Question 69 (1 mark)

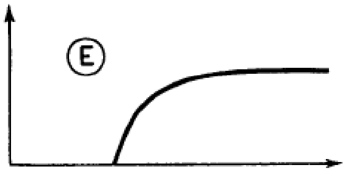
Monochromatic light, of fixed frequency 12 x 10^{14} Hz but variable intensity, is shone onto the magnesium surface. Which of the following graphs best shows the relationship between E_{max} (the maximum kinetic energy of individual electrons) and intensity?











Example 5.10: 1982 Question 48 (1 mark)

Which of the following figures best represent the relationship between V_s and the frequency of the light, f, for four different metals?

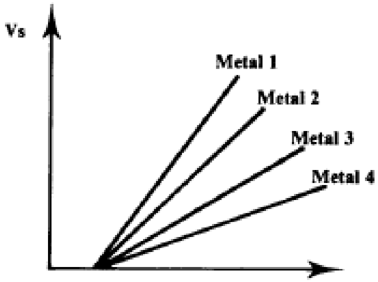


Figure A

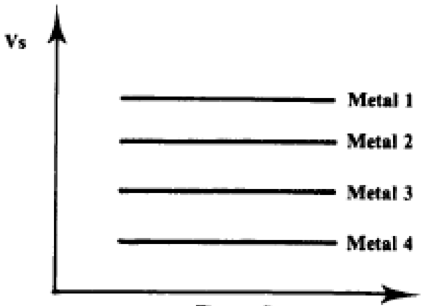


Figure B

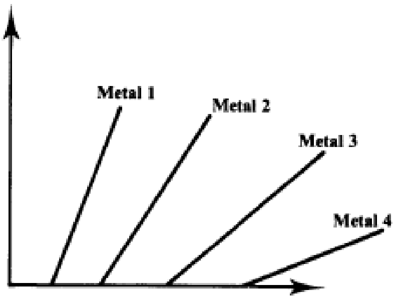


Figure C

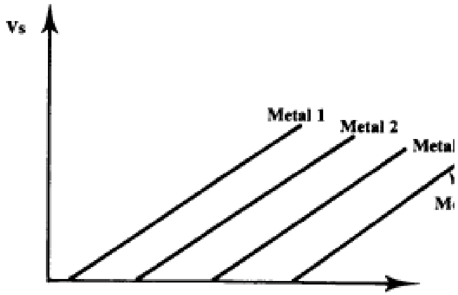


Figure D

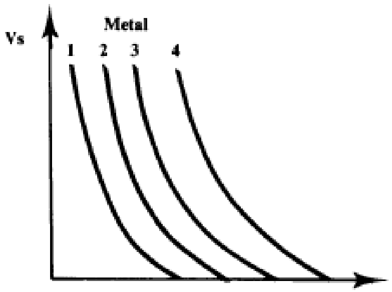


Figure E

Example 5.11: 1982 Question 49 (1 mark)

Blue light of a particular intensity is found to cause photoelectric emission from a sodium surface, but not from a platinum surface. In order to produce photoelectric emission from platinum, which one or more of the following changes would be necessary?

A. Replace the blue light by light of much longer wavelength.

B. Replace the blue light by light of much shorter wavelength.

C. Increase the intensity of the light.

D. Reduce the temperature of the platinum.

(One or more answers)

Example 5.12: 1982 Question 50 (1 mark)

Which of the following best accounts for the difference in behaviour between platinum and sodium?

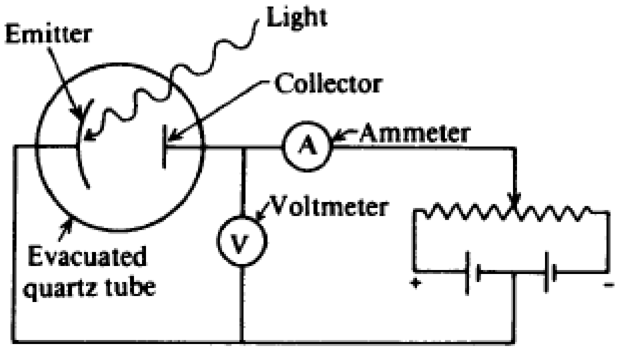
A. Electrons in platinum are less able to capture photons.

B. Platinum has fewer electrons than sodium.

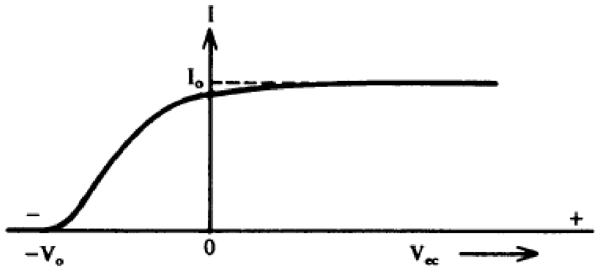
C. More energy is needed to remove an electron from a platinum surface.

D. Photons are able to penetrate a sodium surface more easily.

An apparatus to investigate the photoelectric effect is set up as shown in the figure below. The ammeter measures the current *I* in the circuit, and the voltmeter measures the potential V_{EC} of the collector relative to the emitter. V_{EC} may be made positive or negative as shown.

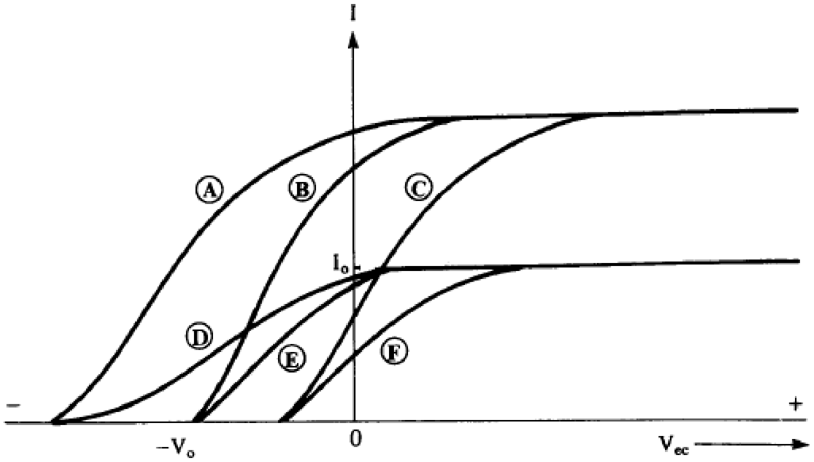


For an emitter made of a particular material and illuminated with light of a fixed intensity and frequency the-following graph of *I* as a function of V_{EC} is obtained. I_o is the current obtained for a very large value of V_{EC}.



Example 5.13: 1985 Question 46 (1 mark)

Which graph (**A** - **F**) below best represents the results expected if the intensity of the light were doubled, using the same emitter and the same frequency of light?

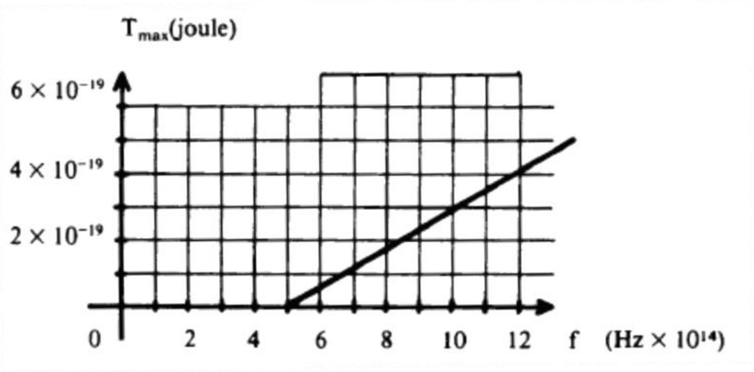


The experiment is repeated using the same emitter but light of a higher frequency. The intensity of light is such that the same number of photons per second falls on the emitter as originally, when obtaining the results.

Example 5.14: 1985 Question 47 (1 mark)

Which of the graphs (**A** - **F**) best represents the results expected?

When ultraviolet light falls on a potassium surface, electrons are emitted from the surface of the metal.



The Kinetic energy T_{MAX} of the most energetic electrons is found to be dependent upon the frequency, *f*, of the radiation used, as shown in the graph above.

Example 5.15: 1986 Question 47 (1 mark)

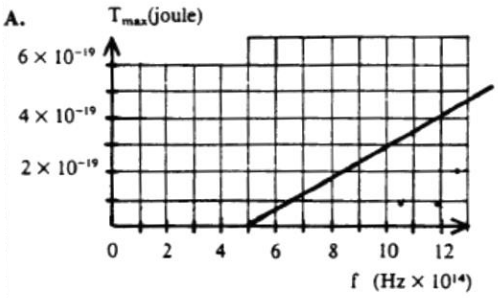
Which of the graphs (**A** - **E**) below, represents the result if the intensity of the light were doubled?

Example 5.16: 1986 Question 48 (1 mark)

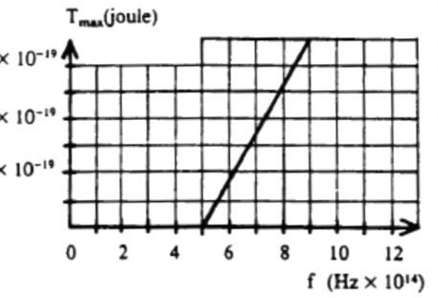
Which *one or more* of the graphs (**A** - **E**) below, could represent the result if the potassium were replaced by another metal?

(one or more answers)

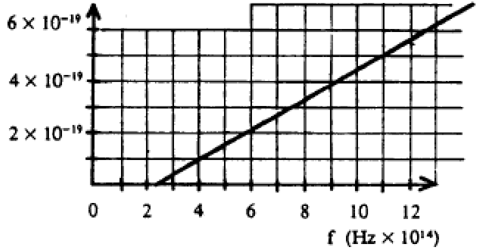
A.


T_{max}(joule)
6×10^{-19}
4×10^{-19}
2×10^{-19}
0
2
4
6
8
10
12
f (Hz × 10^{14})

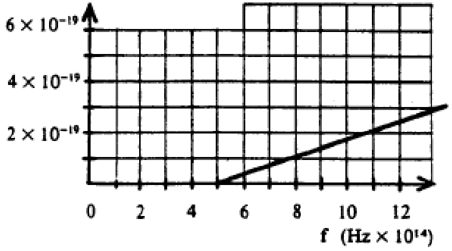
B.


T_{max}(joule)
6×10^{-19}
4×10^{-19}
2×10^{-19}
0
2
4
6
8
10
12
f (Hz × 10^{14})

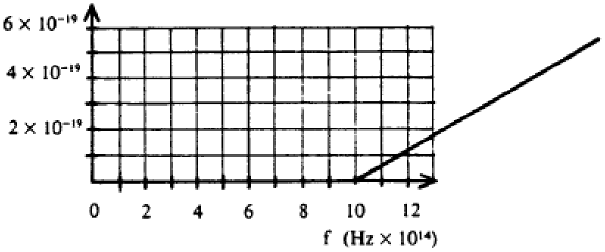
C.


T_{max}(joule)
6×10^{-19}
4×10^{-19}
2×10^{-19}
0
2
4
6
8
10
12
f (Hz × 10^{14})

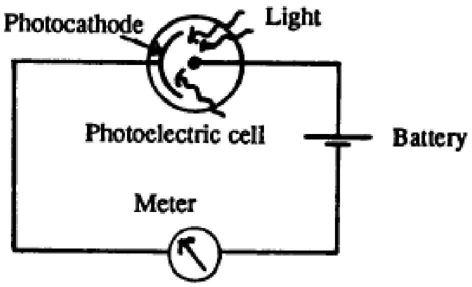
D.

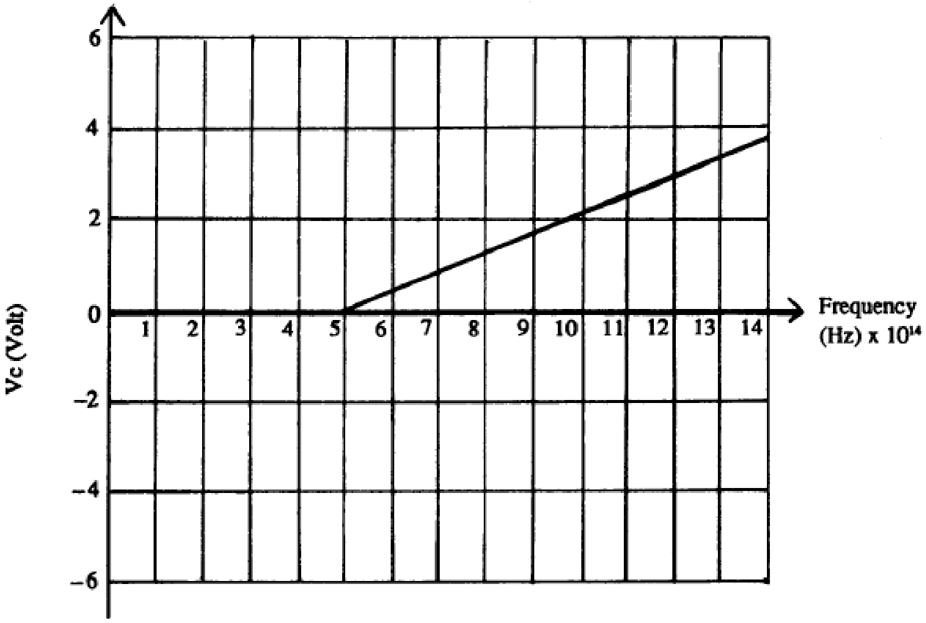

T_{max}(joule)
6×10^{-19}
4×10^{-19}
2×10^{-19}
0
2
4
6
8
10
12
f (Hz × 10^{14})

E.


T_{max}(joule)
6×10^{-19}
4×10^{-19}
2×10^{-19}
0
2
4
6
8
10
12
f (Hz × 10^{14})

The light meter of a particular camera consists of a circuit using a photoelectric cell as shown. The material of the photocathode has a cut off potential versus frequency relationship as given below.





When answering the following questions take h = 4.1 x 10^{-15} eV s.

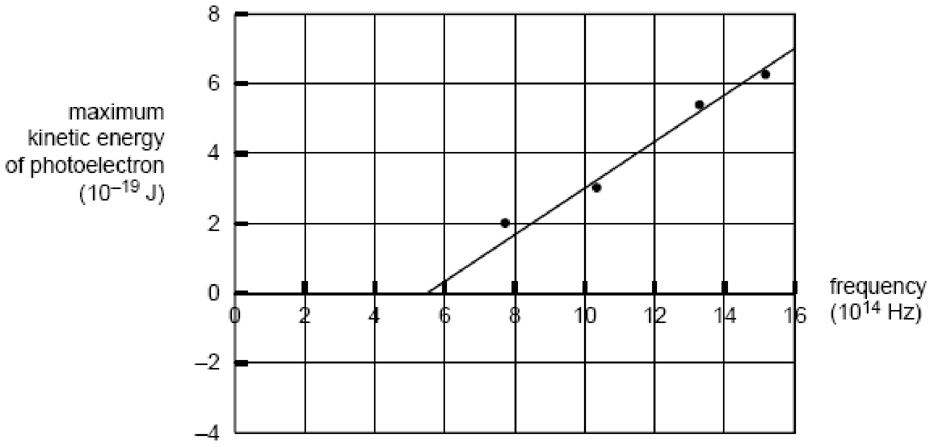
Example 5.17: 1988 Question 29 (1 mark)

What is the work function (in eV) of the cathode material?

Example 5.18: 1988 Question 30 (1 mark)

What is the maximum kinetic energy (in eV) of an ejected electron when light of frequency 7.0 x 10^{14} Hz falls on the photocathode?

A photoelectric effect experiment was performed with a plate of unknown metal. The following graph was formed from the results taken during the experiment.



The cut-off frequency for this metal was found to be 5.5 × 10^{14} Hz.

Example 5.19: 2001 Question 4 (2 marks)

Determine the work function for this metal from the graph. ($h = 6.63 \times 10^{-34}$ J s)

The table below shows the corresponding wavelength for the cut-off frequency for different metal surfaces.

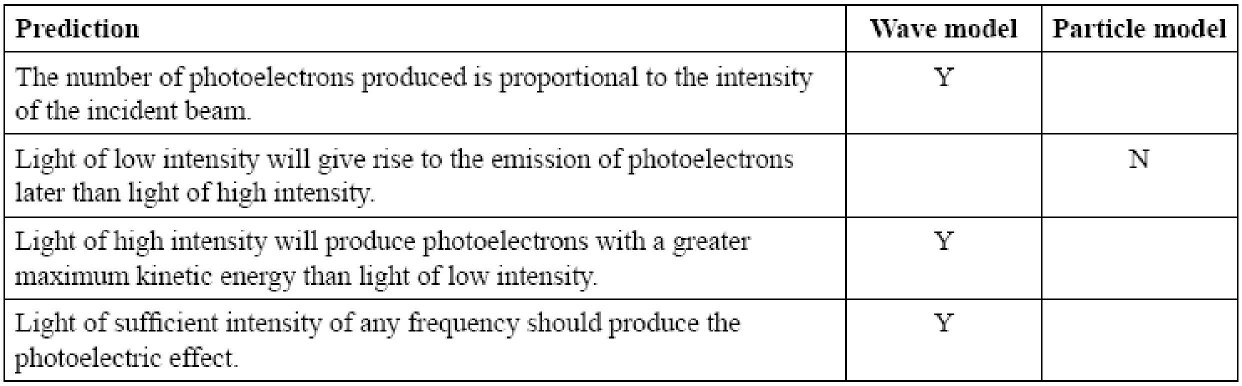
Metal	Wavelength (nm)
Caesium	682
Sodium	545
Zinc	405
Magnesium	345
Aluminium	303

Example 5.20: 2001 Question 5 (2 marks)

What is the metal that was used in the original data?

Example 5.21: 2006 Question 2 (4 marks)

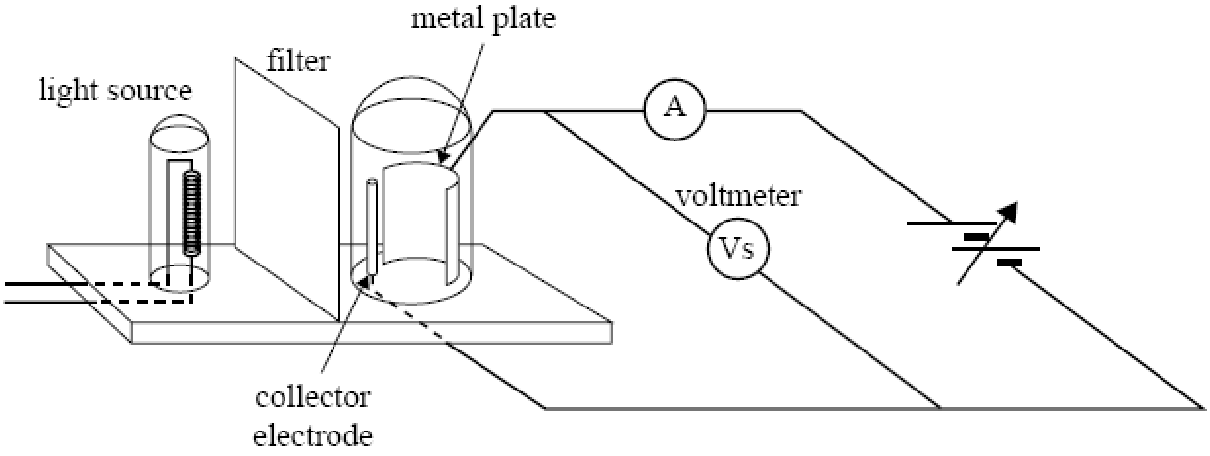
The table below contains some predictions for the behaviour of light incident on a shiny metal sheet. Complete the table by placing a "Y" (Yes) or "N" (No) in the appropriate boxes if the prediction is supported by the wave **and/or** particle model of light. Some answers have already been provided. It is possible for predictions to be supported by both models.



Prediction	Wave model	Particle model
The number of photoelectrons produced is proportional to the intensity of the incident beam.	Y	
Light of low intensity will give rise to the emission of photoelectrons later than light of high intensity.		N
Light of high intensity will produce photoelectrons with a greater maximum kinetic energy than light of low intensity.	Y	
Light of sufficient intensity of any frequency should produce the photoelectric effect.	Y	

To study the photoelectric effect, students use the apparatus shown below.
The apparatus consists of
- a light source
- a filter that allows only certain frequencies to pass
- a metal plate and collector electrode in a vacuum
- a variable DC source, voltmeter and ammeter.

The students shine light of different frequencies onto the metal plate. They measure the stopping (repelling) voltage (Vs) that just stops the emitted electrons reaching the collector.

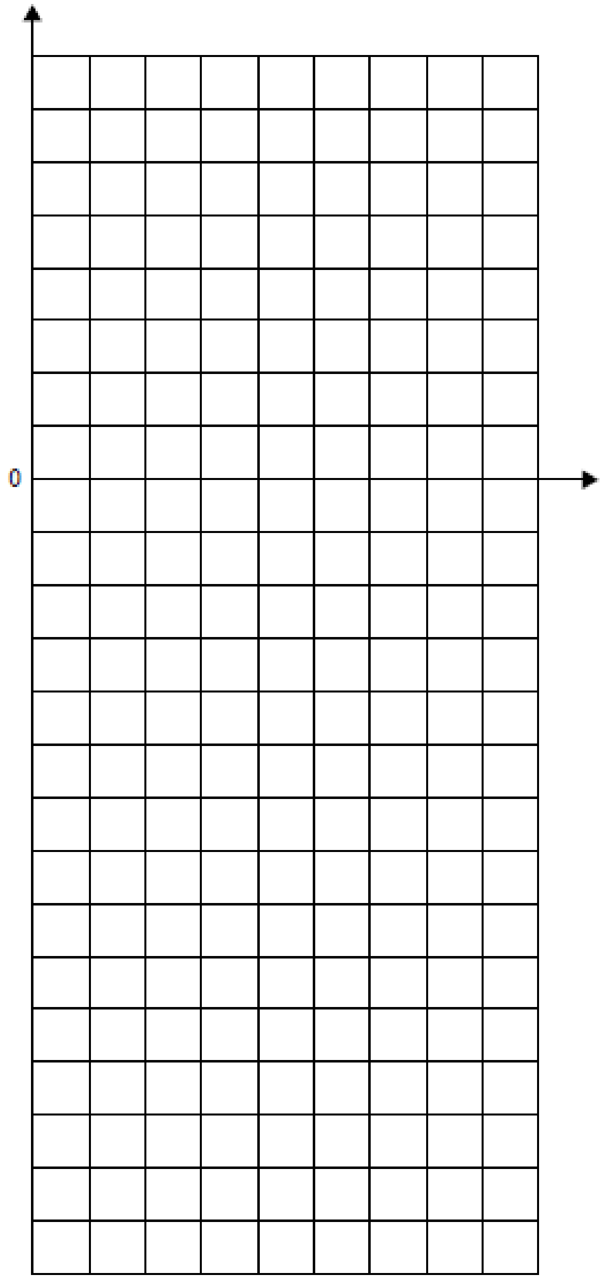


The data that the students gathered is shown in the table following.

Frequency (Hz)	Stopping voltage (Vs)
6.0×10^{14}	0.50
6.6×10^{14}	0.80
7.2×10^{14}	1.10
8.0×10^{14}	1.50

Example 5.22: 2008 Question 6 (3 marks)

Draw a suitable graph from the data above. Label axes and provide units.



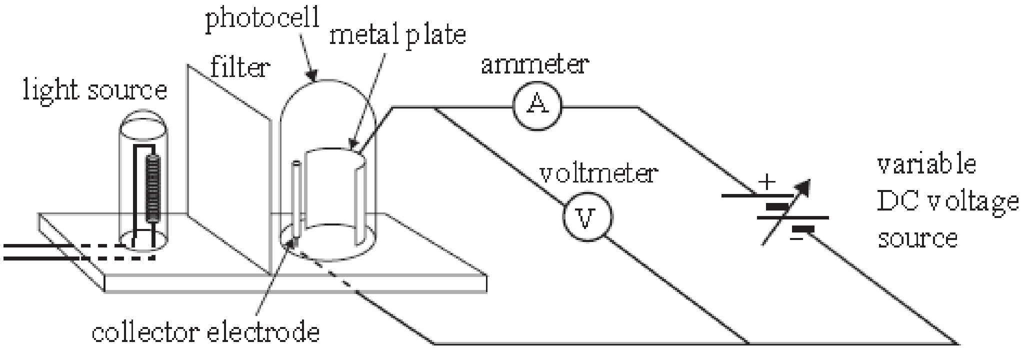
Example 5.23: 2008 Question 7 (3 marks)

What value did the students determine from the graph for Planck’s constant? Include a unit.

Example 5.24: 2008 Question 8 (2 marks)

The work function is the minimum energy (eV) required to remove a photoelectron from a metal. What value did the students determine from the graph for the work function of the metal of the plate?

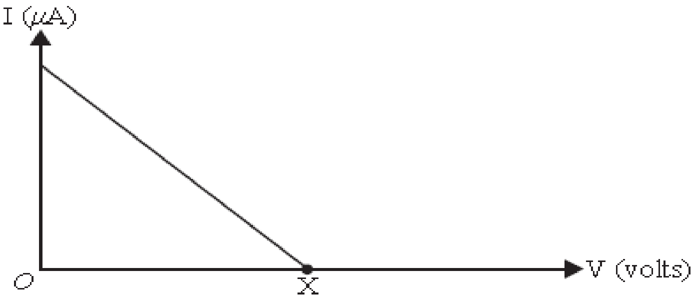
Students set up the apparatus shown below to study the photoelectric effect.



The apparatus consists of

- a source of white light
- a set of filters that only allow light of selected wavelengths to pass through
- a metal plate and a collector electrode enclosed in an evacuated (no air) glass case
- a voltmeter (V), ammeter (A), and variable DC voltage source in a circuit, as shown.

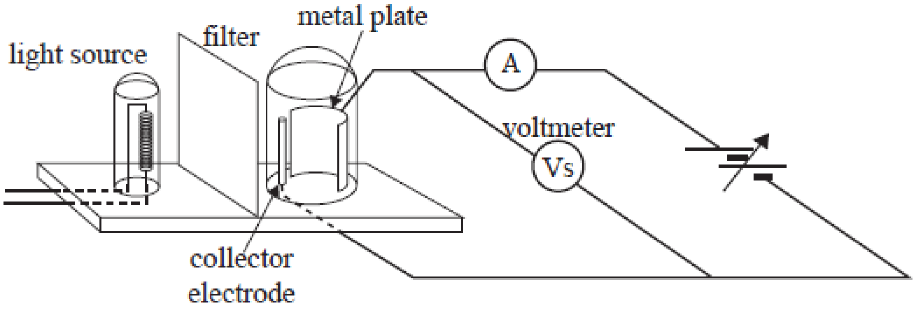
With a particular filter in place, the students gradually increase the voltage as measured by the voltmeter, V, from zero. They plot the current measured through the ammeter, A, as a function of the voltage measured by the voltmeter, V. This is shown below.



Example 5.25: 2011 Question 5 (2 marks)

Explain why the current drops to zero at X.

Vishvi is carrying out photoelectric effect experiments. Her apparatus is shown below.



Vishvi uses two metal plates in the photoelectric cell. One plate is made of zinc and the other is made of aluminium. Vishvi uses light of a particular frequency to illuminate the zinc plate and then the aluminium plate, but finds that photoelectrons are emitted only by the zinc plate.

Example 5.26: 2012 Question 1b (3 marks)

In an effort to eject photoelectrons from the aluminium plate, Vishvi increases the intensity of the light beam, but still finds that no photoelectrons are emitted.

Explain how this observation supports the particle model of light, but not the wave model of light.

In another photoelectric experiment, Vishvi uses light with a frequency of 7.50×10^{14} Hz to eject photoelectrons from a sodium surface. The work function of sodium is 2.28 eV.

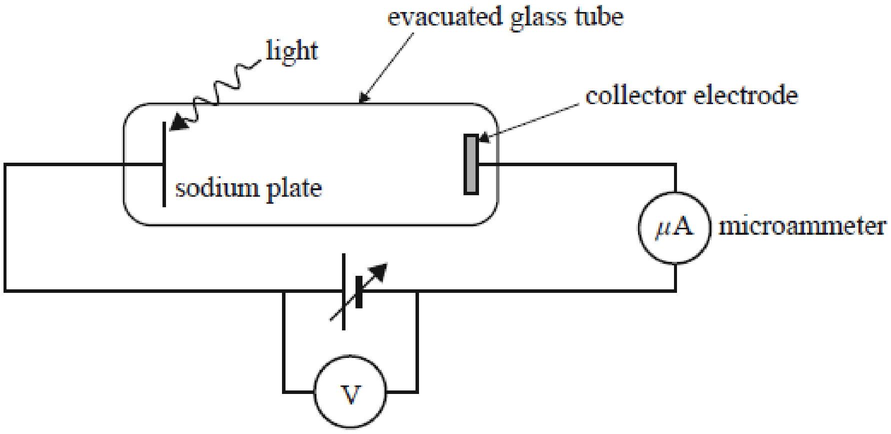
Example 5.27: 2012 Question 1c (3 marks)

Calculate the maximum kinetic energy (in eV) of these photoelectrons.

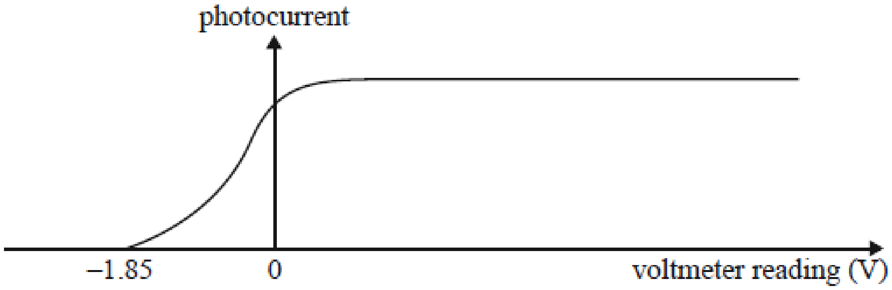
Example 5.28: 2012 Question 1d (1 mark)

Calculate the **stopping voltage** that would be required to just prevent the most energetic electrons from reaching the collector electrode

Students are investigating the photoelectric effect by shining monochromatic light with a frequency of 1.00 × 10^{15} Hz onto a sodium plate. Their apparatus is shown below.



The graph shows the relationship between the photocurrent and the reading on the voltmeter.



Example 5.29: 2013 Question 21a (1 mark)

Use the information in the graph to calculate the maximum kinetic energy (in joules) of the photoelectrons.

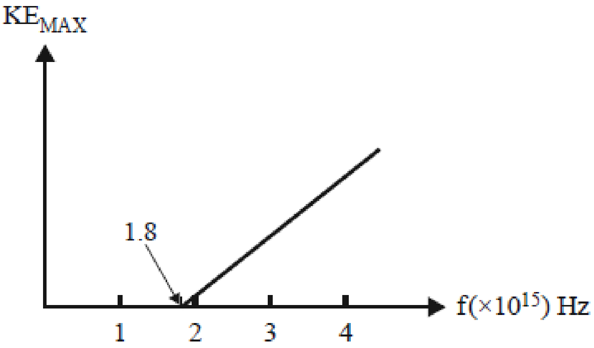
Example 5.30: 2013 Question 21b (2 marks)

Calculate the work function (in eV) of sodium.

Example 5.31: 2013 Question 21d (2 marks)

The students change the light source to one with a different frequency. They observe that the photocurrent is zero and remains at zero regardless of the size or sign of the voltage. Explain this observation.

A group of students carry out an experiment where light of various frequencies is shone onto a metal plate.
The maximum kinetic energy of the emitted electrons for each frequency is recorded and the results are plotted to produce the graph shown. Take Planck's constant as 6.63 × 10^{-34} J s.



Example 5.32: 2014 Question 20b (3 marks)

The intensity of the light is increased and the experiment is repeated with the same frequencies. The students find that the graph of frequency against maximum kinetic energy for this second experiment is exactly the same as for the first experiment.
Explain why this result provides evidence for the particle-like nature of light.

Behaviour of light

- **investigate and describe theoretically and practically the effects of varying the width of a gap or diameter of an obstacle on the diffraction pattern produced by light and apply this to limitations of imaging using light**

Matter as particles or waves

- **interpret electron diffraction patterns as evidence for the wave-like nature of matter**
- **distinguish between the diffraction patterns produced by photons and electrons**
- **calculate the de Broglie wavelength of matter: $\lambda = \frac{h}{p}$.**

Similarities between light and matter

- **interpret the single photon/electron double slit experiment as evidence for the dual nature of light/matter**

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
10, 11	4, 5 6	9		7, 8, 9, 10	10, 11, 12	3a, b	23a, b	21a, b, c, d	20a, b 22	20a, b, c

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Diffraction

When light passes through a narrow aperture, a hole or a slit, it spreads out, i.e. it diffracts, $\propto \frac{\lambda}{d}$.

The wave nature of electrons

If electrons can behave as waves inside an atom, they might be able to exhibit other wave properties like interference. This was shown in electron scattering experiments - definite patterns of reinforcement (antinodes) and reduction (nodes) were found in scattering. The gaps that the electrons were passing through in scattering were very small, in the order of the radius of an atom; hence the electrons wavelengths must be much smaller than that of light.

The wave-like nature of matter

de Bröglie speculated that if light waves could behave like particles, then particles of matter should behave like waves. He argued that the equation $p = \frac{h}{\lambda}$ should apply to particles as well as waves.

Experiments with electrons clearly show that they can diffract and interfere with each other. Protons and neutrons also have been shown to exhibit wave-like behaviour.

The wavelength of a particle of matter could be found by using: $\lambda = \frac{h}{p} = \frac{h}{mv}$

The wavelength is inversely proportional to the momentum. With any mass that is not sub-atomic, the product of 'mv' is so large that λ is always of the order 10^{-33} m, too small for us to see. When sound and light waves pass through narrow slits, they show diffraction effects only when the slit is about 1 – 50 λ. Thus, a particle could be expected to show diffraction only if it is passing through a gap 1 - 50 times its de Bröglie wavelength.

For most large particles this is impractical as the physical size of the particle is far too large. Only in the case of small particles such as electrons, is the de Bröglie wavelength enough for diffraction and interference effects to occur.

Example 5.33: 1971 Question 58 (1 mark)

With reference to the particle model of light propagation, which of the following statements are true?

A. It accounts satisfactorily for reflection at a surface,

B It yields an inverse square law for the decrease in light intensity with distance from a point source,

C It predicts that light which is incident on a surface will exert pressure on that surface.

D It predicts that light will travel more slowly in a refracting material than in a vacuum.

(One or more answers)

Example 5.34: 1971 Question 59 (1 mark)

With reference to the wave model of light propagation, which of the following statements are true?

A. It accounts satisfactorily for both interference and diffraction effects.

B. It predicts that light will travel more quickly in a refracting material than in a vacuum.

C. It accounts satisfactorily for the photoelectric effect

D. It accounts satisfactorily for partial reflection and partial transmission at a surface.

(One or more answers)

Example 5.35: 1973 Question 48 (1 mark)

Which of the following phenomena cannot readily be accounted for by the particle model of light?

A. When light is reflected by a mirror the angle of reflection is equal to the angle of incidence.

B. When light passes through a slit it is diffracted

C. When light passes from air to water it is refracted

D. The intensity of light from a point source decreases with increasing distance from the source.

E. Light exerts a pressure when falling on a surface

Example 5.36: 1976 Question 58 (1 mark)

Sound exhibits wave behaviour. Which of the following statements provides the best evidence for the truth of this statement?

A. Sound can be produced by vibrating objects

B. Sound can be reflected

C. Sound can be refracted

D. Diffraction effects can be readily observed with sound

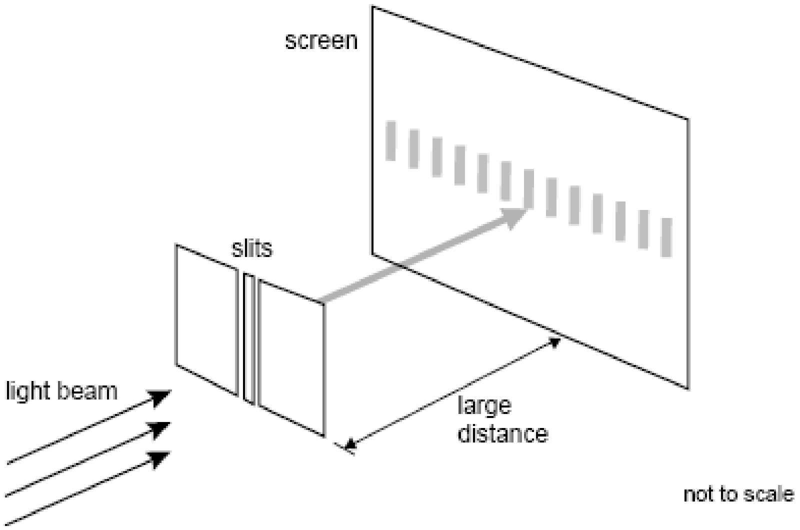
E. Windows can be shattered by sounds of high intensity

F. Sound travels at 300 m s^{-1} in air

Example 5.37: 1976 Question 59 (1 mark)

Sound is not a form of electromagnetic radiation. Which of the above statements is the best evidence for the truth of this statement?

When light of single wavelength passes through two close, narrow slits a pattern of light and dark bands is observed on a screen that is about 2 metres from the slits. The experimental arrangement is illustrated below.



Example 5.38: 1997 Question 4 (1 mark)

Explain, giving reasons, whether the particle model or the wave model for light best explains the observations of this experiment.

Example 5.39: 1998 Question 8 (3 marks)

Calculate the de Bröglie wavelength of electrons with a speed of 1.0×10^7 m s^{-1}.

Example 5.40: 2001 Question 2 (3 marks)

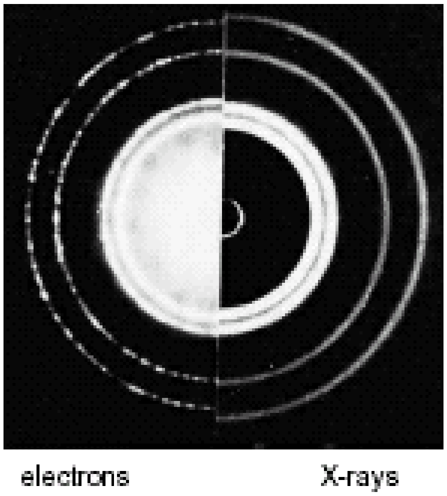
Calculate the de Bröglie wavelength of an electron after being accelerated across 10 kV.

Example 5.41: 2003 Question 4 (3 marks)

Katie and Jane are discussing wave-particle duality. Jane wonders whether wave-particle duality might explain why she missed hitting the softball in a recent match – maybe the wave nature of the softball allowed it to diffract around the bat! Katie said that this was not a reasonable explanation and that we cannot see the wave nature of a softball. A softball has a mass of 0.20 kg and the pitcher throws it at about 30 m s^{-1}.

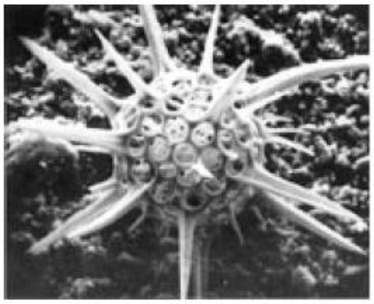
Explain to Jane, using an appropriate calculation, why she would be unable to see the wave nature of a moving softball.

Electron Diffraction Patterns

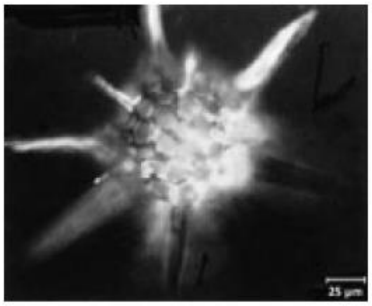


One experiment that is used to show the wave nature of electrons is the electron diffraction pattern. Electrons are sent through a piece of metal as they pass through they leave a pattern on a screen. Only half of the pattern is projected onto the screen, then x-rays are sent through the metal and the pattern from the x-rays is projected onto the other half of the screen. If the two patterns align then the x-rays must have the same wavelength as the electrons.
The pattern is formed from diffraction as the wave fronts travel between the atoms. Then the wavefronts interfere with each other to form bright and dark rings.

The two images below show a radiolarian, a unicellular organism, taken with an electron microscope and an optical microscope. The electron microscope gives a clearer image than the optical microscope.



radiolarian, electron microscope



radiolarian, optical microscope

Example 5.42: 2001 Question 3 (3 marks)

Explain why the electron microscope gives a clearer image than the optical microscope.

The wave-like nature of individual photons

Water waves and sound waves demonstrate interference by interacting with each other. With photons it is not quite so straight forward. When the double slit experiment is performed using light, it is possible to lower the intensity so that only one photon of light passed through the slits at a time. (this was done by Taylor) i.e., there was no chance of the photons interacting, but interference was still observed.

A series of bright and dark bands were eventually formed on the photographic plate that was being used. The pattern of interference was an interference pattern as predicted by the wave model. The photons behave like particles in that they go through either one slit or the other, but they don't form a pattern consisting of two narrow lines that you would expect from particles. The photons don't interact with each other, yet after passing through the slit each photon has a high probability of heading towards one of the bright bands.

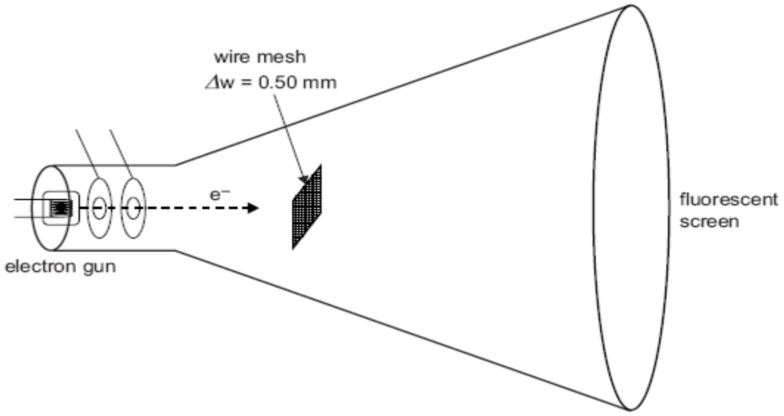
Example 5.43: 1998 Question 6 (2 marks)

When a beam of light passes through a very narrow single slit a pattern is produced on a screen.
Explain what this pattern tells us about the nature of the individual photons that make up the beam of light.

Wave-particle duality of light

The argument about whether light was a wave or a particle was settled in the 1920's. The wave model explained refraction, diffraction and interference of light. The particle model explained the photoelectric effect. Light is neither a wave nor a particle. Photons exhibit both wave and particle properties. This is called WAVE-PARTICLE DUALITY.

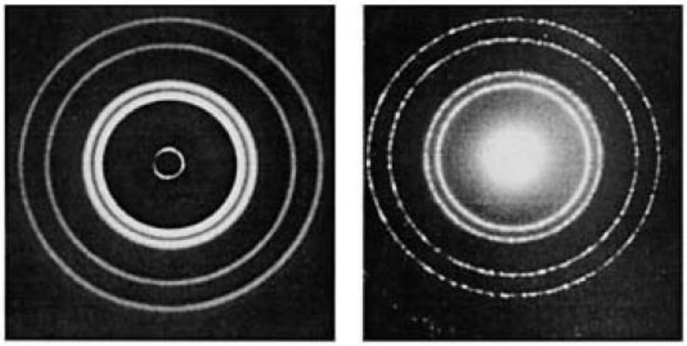
A sketch of a cathode ray tube (CRT) is shown below. In this device, electrons of mass 9.10×10^{-31} kg are accelerated to a velocity of 2.0×10^{7} m s^{-1}. A fine wire mesh in which the gap between the wires is w = 0.50 mm has been placed in the path of the electrons, and the pattern produced is observed on the fluorescent screen.



Example 5.44: 2005 Question 6 (3 marks)

Calculate the de Broglie wavelength of the electrons. You must show your working.

A beam of X-rays, wavelength λ = 250 pm (250×10^{-12} m), is directed onto a thin aluminium foil. The X-rays scatter from the foil onto the photographic plate. After the X-rays pass through the foil, a diffraction pattern is formed as shown in the figure on the left.
In a later experiment, the X-rays are replaced with a beam of energetic electrons. Again, a diffraction pattern is observed which is very similar to the X-ray diffraction pattern.
This is shown in the figure on the right.



Example 5.45: 2006 Question 11 (3 marks)

Assuming the two diffraction patterns are identical, estimate the momentum of the electrons. Include the unit.

Neutrons are subatomic particles and, like electrons, can exhibit both particle-like and wave-like behaviour. A nuclear reactor can be used to produce a beam of neutrons, which can then be used in experiments.
The neutron has a mass of 1.67×10^{-27} kg.
The neutrons have a de Broglie wavelength of 2.0×10^{-10} m.
The neutron beam is projected onto a metal crystal with interatomic spacing of 3.0×10^{-10} m.

Example 5.46: 2007 Question 5 (2 marks)

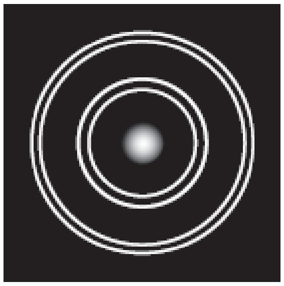
Would you expect to observe a diffraction pattern? Explain your answer.

X-rays of wavelength 0.20 nm are directed at a crystal and a diffraction pattern is observed. The X-ray beam is replaced by a beam of electrons. A similar diffraction pattern is observed with the same spacing.

Example 5.47: 2011 Question 11 (2 marks)

What must be the energy, in eV, of each electron to produce this pattern?

A beam of electrons is travelling at a constant speed of 1.5×10^5 m s^{-1}. The beam shines on a crystal and produces a diffraction pattern. The pattern is shown below. Take the mass of one electron to be 9.1×10^{-31} kg.

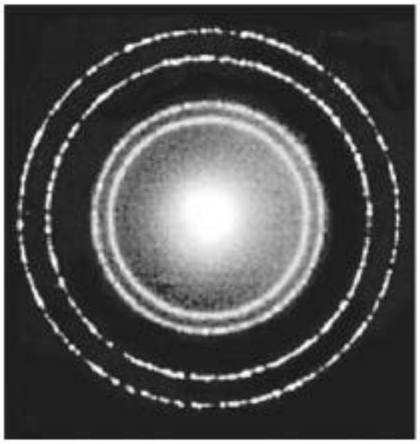


The beam of electrons is now removed and replaced by a beam of X-rays. The resulting pattern has the **same spacing** as that produced by the electron beam.

Example 5.48: 2012 Question 3b (3 marks)

Calculate the energy (in eV) of one X-ray photon.

Students aim X-rays with a photon energy of 80 keV at a thin metal foil. The resulting diffraction pattern is shown below.



Example 5.49: 2013 Question 23a (2 marks)

Calculate the magnitude of the momentum of a single X-ray photon.

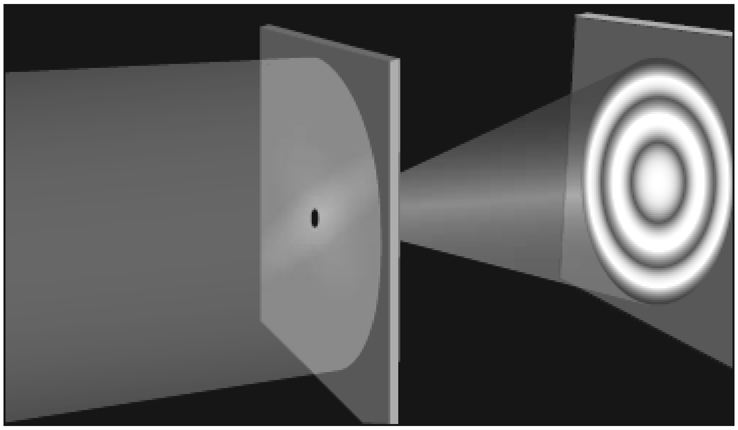
Example 5.50: 2013 Question 23b (3 marks)

The students are aware that electrons can also be used to form diffraction patterns. They wish to use a beam of electrons to form a diffraction pattern with fringe spacings identical to those previously.

Student A says that the fringe spacing will be identical if the electrons have the same momentum as the X-rays. Student B says that the fringe spacing will be identical if the electrons have the same energy as the X-rays.

Which student is correct? Explain your answer.

Thuy is doing some experiments on the diffraction of photons. She is using a beam of photons with an energy of 4.1 eV.
The beam is incident on a small circular aperture and the resulting diffraction pattern is produced on a photon-sensitive screen behind the aperture. This pattern is shown below.



A second experiment is then performed with the same light beam incident on a circular aperture with a larger diameter.

Example 5.51: 2014 Question 21b (1 mark)

Complete the following sentence by circling the correct words that are shown in **bold** font.

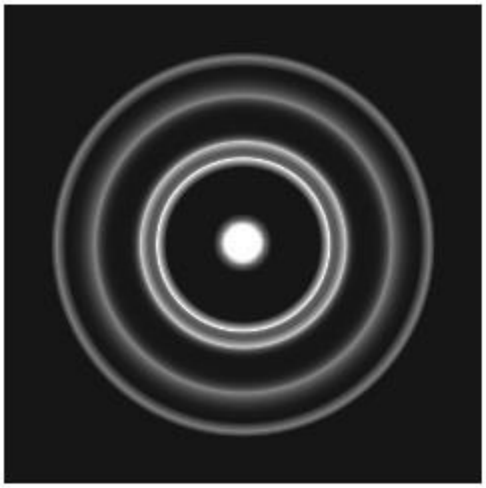
Corresponding rings in the second diffraction pattern would have diameters that are

larger than / the same size as / smaller than the rings in the original pattern.

Example 5.52: 2014 Question 21c (2 marks)

Give your reasoning for your answer to **part b.**

Thuy now carries out another experiment, comparing the diffraction of X-ray photons and electrons.
A beam of X-ray photons is incident on a small circular aperture. The experiment is then performed with a beam of electrons incident on the same aperture.
The X-ray photons and electrons have the same energy. The diffraction patterns have the same general shape, but very different spacings.



X-ray photon diffraction

electron diffraction

not to scale

Example 5.53: 2014 Question 21d (3 marks)

Explain why the electron diffraction pattern has a different spacing from the X-ray diffraction pattern, even though the electrons and the photons have the same energy.

Physicists use the expression ‘wave-particle duality’ because light sometimes behaves like a particle and electrons sometimes behave like waves.

Example 5.54: 2015 Question 20b (2 marks)

What evidence do we have that electrons can behave like waves? Explain how this evidence supports a wave model of electrons.

Similarities between light and matter

- **compare the momentum of photons and of matter of the same wavelength including calculations using: $p = \frac{h}{\lambda}$**

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
			8, 9							

Photons

The modern theory of light is a merging of the wave and the particle models. Light is modelled as a stream of packets or *quanta* of energy. The energy carried by each quantum is proportional to the frequency of light and can be found from Planck's equation: $E = hf = \frac{hc}{\lambda}$. Greater intensity of light has more quanta - each quantum still has the same energy. The quanta of energy are called photons.

Photons are neither particles nor waves.

Low frequency photons such as radio-waves and microwaves exhibit distinctly wave-like behaviours such as diffraction and interference, but have no particle-like properties. Around the middle of the spectrum in the visible light region, photons have both wave and particle properties. They interfere and diffract like waves, and also interact with electrons in the photoelectric effect as particles do. At the high frequency end of the spectrum, X-ray and gamma ray photons behave much more like particles than waves.

A helium-neon laser has a power output of 1.0 mW and produces monochromatic red light of wavelength 640 nm.

Example 5.55: 1998 Question 4 (2 marks)

Calculate the energy of a single photon of red light emitted from the laser. ($h = 6.63 \times 10^{-34}$ J s)

Example 5.56: 1998 Question 5 (2 marks)

Calculate the number of photons per second emitted by the laser.

The momentum of photons

In 1923, Compton showed that X-ray photons could collide with electrons and scatter, leaving with a longer wavelength (less energy) than before. This is only possible if the photons were able to transfer momentum and hence energy to the electrons.

Maxwell suggested that photons do have momentum given by

$p = \frac{E}{c}$ *where c is the speed of light and E is the energy of the photon.*

As the energy of the photon is related to its frequency by Planck's equation, and, since $v = f\lambda$ for waves, the momentum equation can be written as $p = \frac{hf}{c} = \frac{h}{\lambda}$

A 10^{-18} J photon has a wavelength of about 2.0×10^{-7} m. Electrons can exhibit wave-like properties very similar to such photons, if they have the appropriate momentum. ($h = 6.63 \times 10^{-34}$ J s).

Example 5.57: 1997 Question 6 (2 marks)

Calculate the value of the momentum of one of these electrons. Give your answer to two significant figures.

Example 5.58: 2009 Question 9 (2 marks)

A source is designed to produce X-rays with a wavelength of 1.4×10^{-10} m. What is the momentum of one of these X-ray photons?

Similarities between light and matter

- **explain the production of atomic absorption and emission line spectra, including those from metal vapour lamps**
- **interpret spectra and calculate the energy of absorbed or emitted photons: $\Delta E = hf$**
- **analyse the absorption of photons by atoms, with reference to:**
  - **– the change in energy levels of the atom due to electrons changing state**
  - **– the frequency and wavelength of emitted photons: $E = hf = \frac{hc}{\lambda}$**

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
5, 6	7, 8, 9	10, 11, 12	10, 11	11	13	4a, b	20a, b	22a, b	19a, b	21a, b, c

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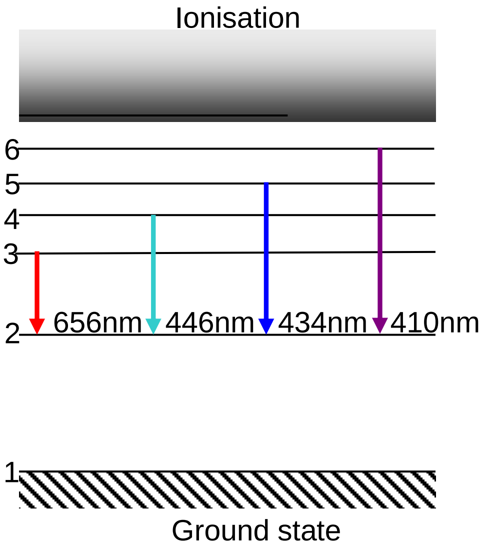
Energy levels in hydrogen

The ionisation energy for hydrogen is 13.6 eV. The ground state energy, level = 0 eV,

Bohr found that $E_n = E_I - \frac{E_i}{n^2}$ (**not on course**)

Where E_n = the energy associated with a particular energy level of hydrogen
E_I = ionisation energy, which is 13.6 eV for hydrogen
n = any whole number, ie, 1, 2, 3 …

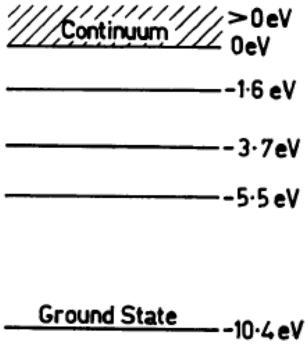
Photons can be emitted or absorbed.
Below are the absorption and emission lines for hydrogen (in the visible region).




Photon absorption


Photon emission

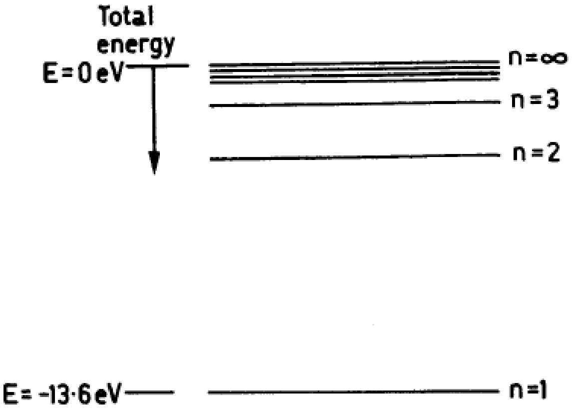
The energy levels of atomic mercury are shown in the following diagram.



Example 5.59: 1973 Question 103 (1 mark)

A photon strikes a mercury atom in its ground state and a photoelectron is ejected with kinetic energy 30.4 eV. What was the energy of the incident photon?

The energy level diagram for the hydrogen atom is drawn below:



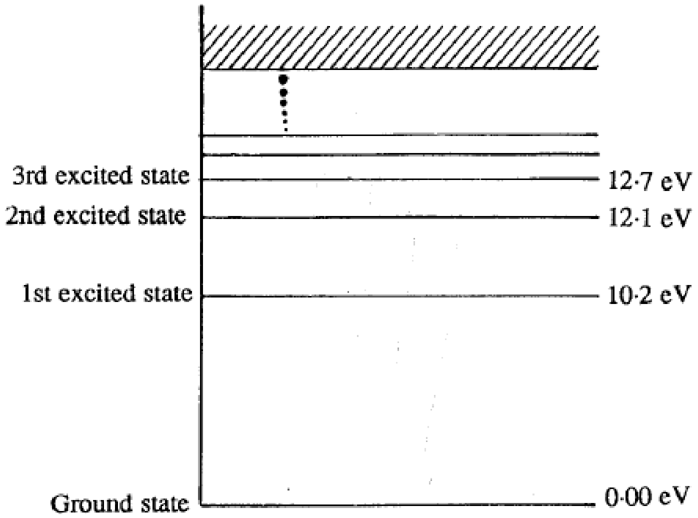
Example 5.60: 1978 Question 77 (1 mark)

What is the value of n for the ground state energy level of the hydrogen atom?

Example 5.61: 1978 Question 78 (1 mark)

What is the energy required to ionize a hydrogen atom originally in its ground state?

The figure below is the energy level diagram for a hydrogen atom.



In an experiment, hydrogen atoms are excited to the 3rd excited state and then decay. Ultimately, all atoms return to the ground state. As a result of these decays, photons of various energies are emitted.

Example 5.62: 1989 Question 65 (1 mark)

How many different photon energies could be observed in this process?

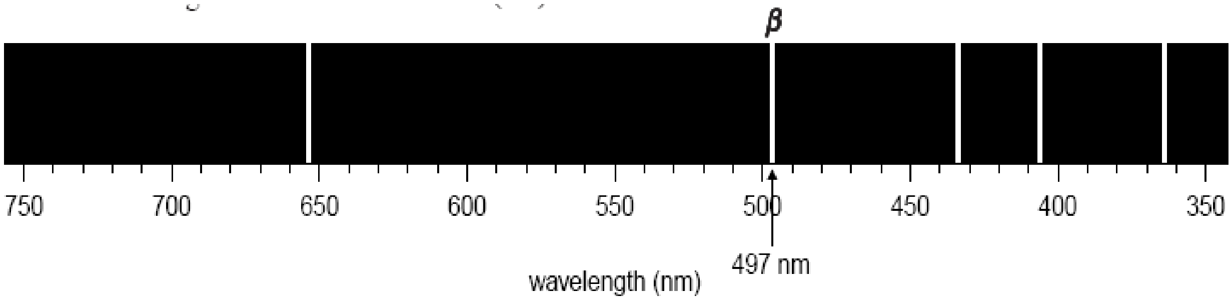
A. 1 **B.** 2 **C.** 3

D. 4 **E.** 5 **F.** 6

Example 5.63: 1989 Question 66 (1 mark)

What is the highest frequency of radiation (in Hz) emitted in this process?
(Planck's constant, h = 4.135×10^{-15} eV s.)

The figure below is part of the emission spectrum for hydrogen taken from sunlight. Each emission line is displayed with the wavelength in units of nanometres (nm).

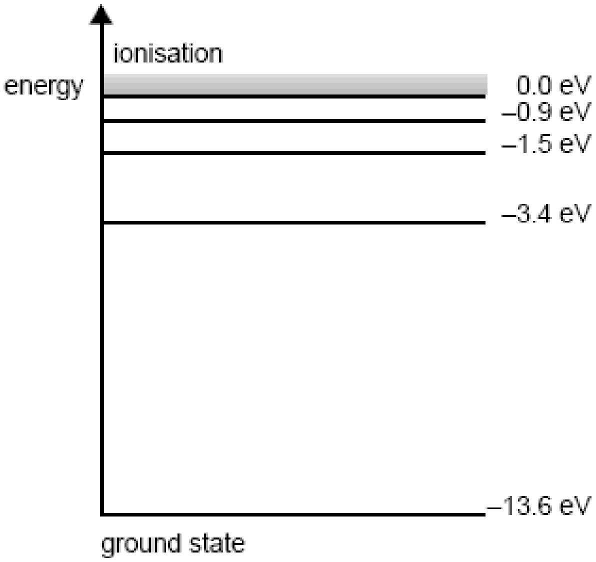


Example 5.64: 2001 Question 6 (2 marks)

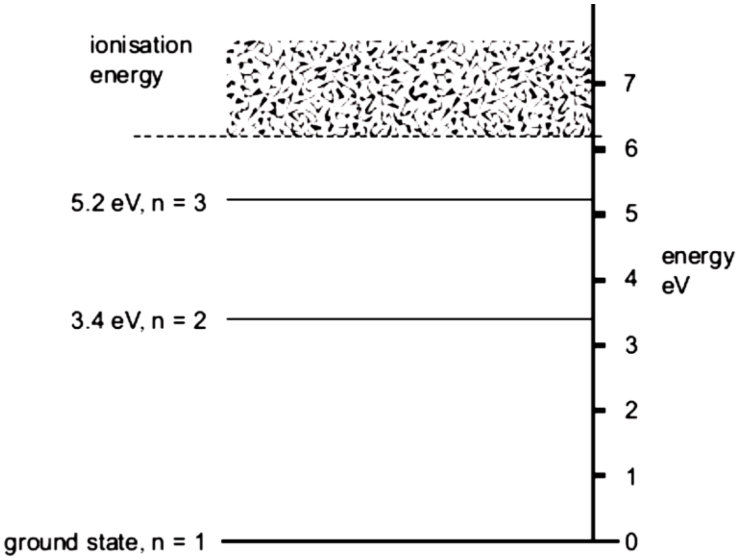
Calculate the energy of the photon, in eV, that is indicated by the spectral line marked β in the figure.

Example 5.65: 2001 Question 7 (2 marks)

On the energy level diagram for hydrogen below, indicate with an arrow (↓) the energy level transition for the spectral line marked β above.



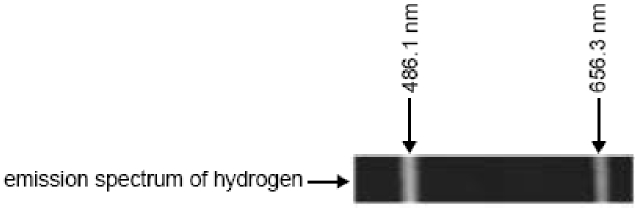
The spectrum of photons emitted by excited atoms is being investigated. Shown below is the atomic energy level diagram of the particular atom being studied. Although most of the atoms are in the ground state, some atoms are known to be in n = 2 and n = 3 excited states.



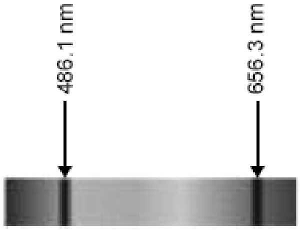
Example 5.66: 2005 Question 10 (2 marks)

Calculate the wavelength of the photon emitted when the atom changes from the n = 2 state to the ground state (n = 1).

The figure below shows part of the emission spectrum of hydrogen in more detail.



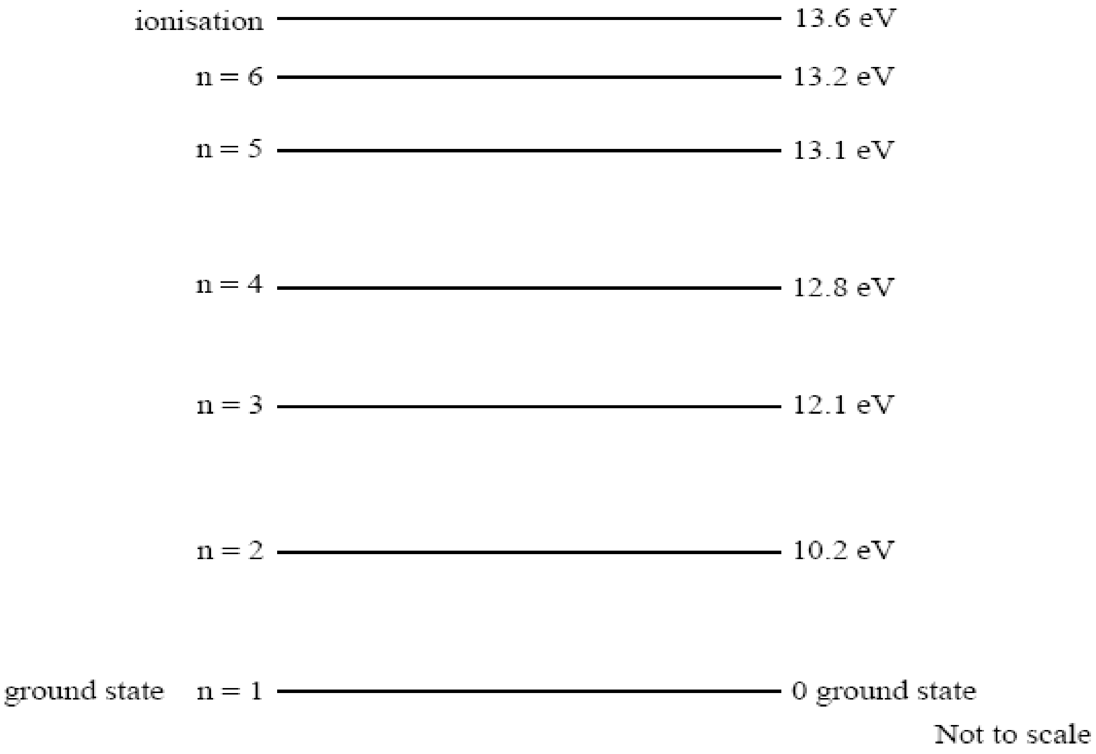
With a spectroscope, Val examines the spectrum of light from the sun. The spectrum is continuous, with colours ranging from red to violet. However there were black lines in the spectrum, as shown below.



Example 5.67: 2007 Question 9 (3 marks)

Explain why these dark lines are present in the spectrum from the sun.

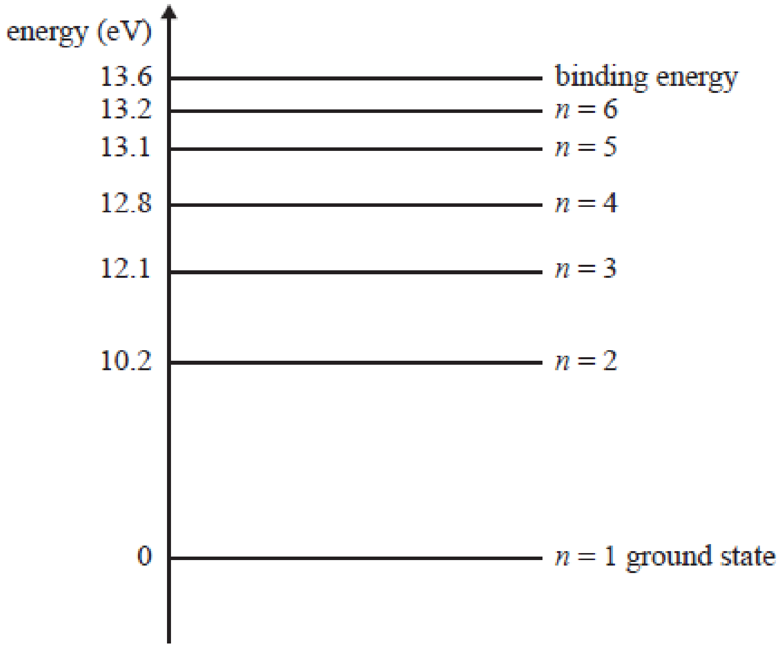
The figure below shows the quantised energy levels in the hydrogen atom, relative to the ground state.



Example 5.68: 2008 Question 12 (2 marks)

What is the shortest wavelength photon that can be emitted when an atom decays from the n = 4 level?

The figure below shows the energy level diagram for the hydrogen atom.

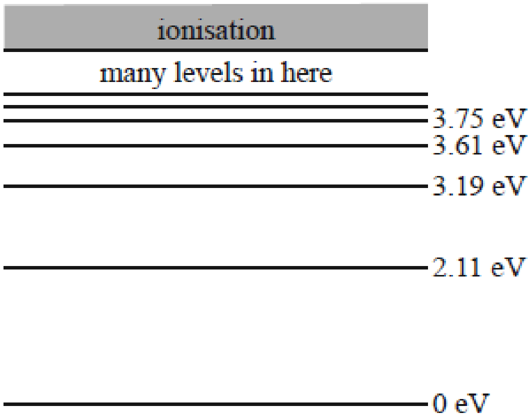


The energy levels of the hydrogen atom are discrete (quantised) and there are no stable levels between them.

Example 5.69: 2012 Question 4b (3 marks)

In terms of the properties of the electron, explain why only certain energy levels are stable.

An energy-level diagram for a sodium atom is shown below.



Example 5.70: 2013 Question 20a (2 marks)

An atom is in the 3.19 eV state. It returns to the ground state, emitting one or more photons. Calculate the **longest** wavelength of light that could be emitted by the atom.

Example 5.71: 2013 Question 20b (3 marks)

Explain, with a calculation, why the emission spectrum of sodium shows a spectral line at 588.63 nm.

Similarities between light and matter

- **describe the quantised states of the atom with reference to electrons forming standing waves, and explain this as evidence for the dual nature of matter**

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
			12				19a, b	23a, b	21a, b	

Quantum physics

Max Planck proposed that energy travels in discrete packets called quanta. Prior to Planck's work, energy was thought to be continuous, but this theory left many phenomena unexplained. In 1900 Max Planck began to study the range of electromagnetic radiation that emanates from a very hot body (black body radiation). When a body is heated, it first glows red; with further heating it turns to white and eventually blue (ie. the wavelength of light emitted becomes shorter and it frequency becomes higher with increasing temperature).

He found that $E = \frac{hc}{\lambda}$ c = speed of light **or** E = hf f is the frequency of the light.

Quantised energy levels in atoms - the Bohr model

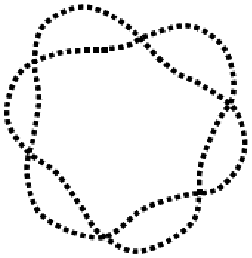
The model for the atom that Rutherford proposed in 1911, that the atom consisted of a small dense, positively charged nucleus surrounded by a cloud of electrons, has a weakness because the accelerating electrons should radiate energy and spiral into the nucleus.

In 1913, Bohr, said that the electrons should not be considered to be orbiting like planets. He said that they simply existed outside the nucleus with certain amounts of energy. According to Bohr, the electrons in the atom existed in certain discrete ENERGY LEVELS.

- Each element has certain allowed energy levels that are unique to that element.
- Electrons can only exist in one of these allowable energy levels, not in between. Ie. energy levels are quantised.
- If an electron is given extra energy it can move up to a higher energy level by absorbing an amount of energy equal to the difference between the energy levels.
- When an electron in a higher energy level returns to its normal (ground state) energy level, it emits the energy in the form of a photon. The energy of the photon ($E = h\nu$) is equal to the difference in energy levels the electron moves between.

Example 5.72: 2004 Sample Question 11 (2 marks)

The pattern below is meant to represent the 'standing wave-state' of an electron in a hydrogen atom. Which value of 'n' would best describe this pattern?



Example 5.73: 2005 Question 11 (3 marks)

Describe how the wave-particle duality of electrons can be used to explain the quantised energy levels of the atom.

Example 5.74: 2009 Question 12 (2 marks)

De Broglie suggested that the quantised energy states of the atom could be explained in terms of electrons forming standing waves.

Describe how the concept of standing waves can help explain the quantised energy states of an atom. You may include a diagram.

According to one model of atoms, electrons in atoms move in stable circular orbits around the nucleus.

In an atom modelled in this way, an electron is moving at 2.0×10^{6} m s^{-1}. Take the mass of an electron as 9.1×10^{-31} kg.

Example 5.75: 2014 Question 23b (3 marks)

Describe how the wave nature of electrons can be used to explain the quantised energy levels in atoms.

Example 5.76: 2015 Question 21a (3 marks)

Use the model of quantised states of the atom to explain why only certain energy levels are allowed.

Example 5.77: 2015 Question 21b (2 marks)

Illustrate your answer with an appropriate diagram.

Similarities between light and matter

- **explain how diffraction from a single slit experiment can be used to illustrate Heisenberg's uncertainty principle**
- **explain why classical laws of physics are not appropriate to model motion at very small scales.**

2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016

Heisenberg's uncertainty principle

Quantum physics (not classical physics), assumes that a matter wave, like a light wave, is a probability wave. Heisenberg proposed that measured values cannot be given to position (x) and momentum (p) of a particle simultaneously with unlimited precision.

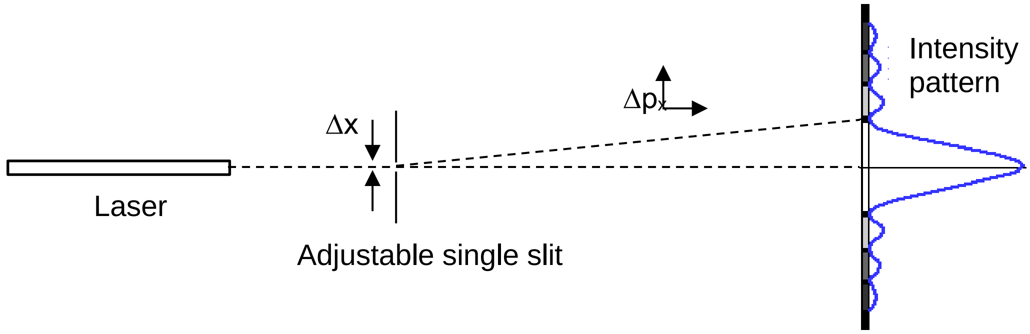
This uncertainty is an outcome of both wave-particle duality and the interactions between the object being observed and the effect of the observation on that object. For the normal 'nonquantum' world Δx and Δp_x are so small they are considered insignificant, but at the atomic scale, this level of uncertainty is significant.

To measure the precise location of a free particle (e.g. electron), it needs to be hit with another particle (e.g. photon). This will cause the electron to move (or move differently) as energy is transferred from the photon. Therefore the act of measuring causes a change in the value of what is being measured. If Δx is position uncertainty, and Δp momentum uncertainty then use $\Delta x \times \Delta p_x \geq \frac{h}{4\pi}$ to find the minimum uncertainty allowed. As Δx decreases Δp_x has to increase.

Single slit diffraction.

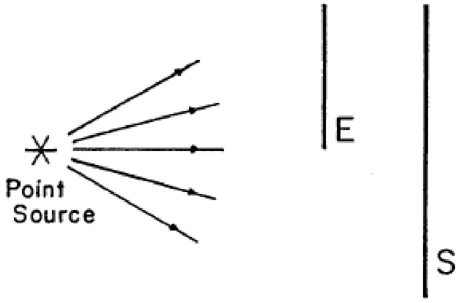
Taylor carried out the single slit experiment using light so feeble that only one photon passed randomly through the slit at a time. Interference fringes built up on the screen (over 3 months), even though the photons could not have been interacting with each other.

As the photon passes through the slit, Δx is the slit width, its position is known with some uncertainty. Heisenberg says that this introduces some uncertainty Δp_x, so beam spreads out, hence the interference pattern. If Δx is smaller, Δp_x must be greater so beam spreads out more.



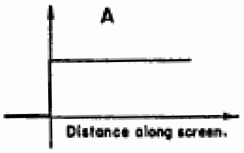
Davisson and Germer (1928) demonstrated the wave nature of electrons, so single slit diffraction can also be observed with particles, e.g. electrons, protons, neutrons etc.

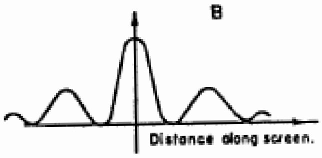
Light from an *Intense* point source is directed at a straight edge E and the variation of light intensity is recorded photographically on the screen S as shown below.

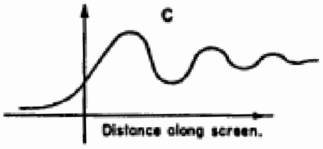


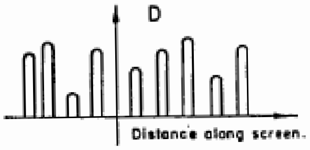
Example 5.78: 1969 Question 107 (1 mark)

A photon counting device (e.g. a photo-cell) traverses the screen extremely slowly, recording the photons striking a small area. Which of the following graphs best represents the number of photons detected per unit time as a function of position along the screen?









Example 5.79: 1969 Question 108 (1 mark)

If the photon counting device is held in a fixed position it would be found that:

A. the time between successive photon arrivals would be constant.

B. the time taken to count the first five photons would be the same as that taken to count the second five photons and so on.

C. the photons arrive at random times.

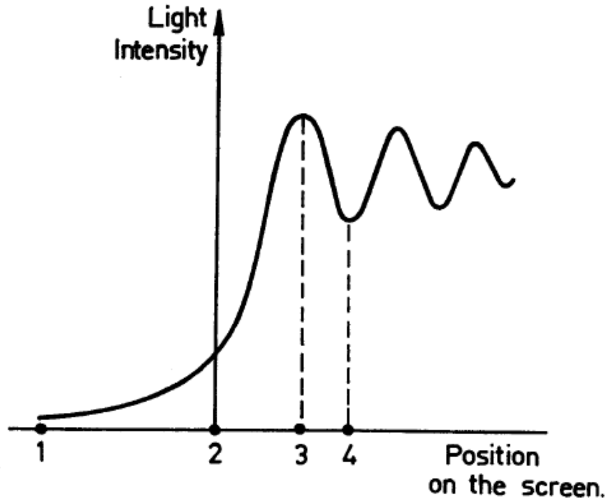
Example 5.80: 1969 Question 109 (1 mark)

The light intensity is now reduced so that there is usually only one photon between the source and the screen at a particular time. A photographic plate, placed on the screen, is exposed *for a long time.* Which of the above graphs best represents the light intensity distribution recorded by the photograph?

Example 5.81: 1969 Question 110 (1 mark)

Instead of photons, an intense narrow beam of electrons is directed at a straight edge as shown above. Which of the above graphs best represents the electron intensity on the screen, plotted against distance along the screen?

The shadow of a sharp edge is thrown on a distant screen. The variation of light intensity with position on the screen is shown on the graph.



Example 5.82: 1971 Question 107 (1 mark)

At which position on the screen is there the greatest probability of photon arrival?

A. Point 1.

B. Point 2.

C. Point 3.

D. Point 4.

Now consider that the intensity of the light source is reduced so that there is, at any one time, only a single photon passing between the light source and the screen. A photographic film is attached to the screen and exposed for a long time.

Example 5.83: 1971 Question 108 (1 mark)

The photographic record of intensity variation with position. will

A. indicate an intensity variation typical of Young's interference experiment.

B. indicate a constant intensity.

C. indicate a gradually decreasing intensity, consistent with the inverse square law.

D. be of the same form as shown on the graph above.

Production of light from matter

- **compare the production of light in lasers, synchrotrons, LEDs and incandescent lights.**

2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
2, 3, 4, 11	1, 2, 3, 4	1, 2, 3, 4	1, 2, 10	1, 4	1, 2, 3, 4	1, 2, 3, 4	1, 2, 3	4, 5, 6, 7	1, 2, 3	1, 2, 3

Lasers

Light emitted by a common lamp is incoherent, that is, photons of many frequencies and in many phases of vibration are emitted. A beam of incoherent light spreads out after a short distance, becoming wider and less intense with increased distance.

Even if the beam is filtered so that it is formed with a single frequency waves (monochromatic), it is still incoherent, for the waves are out of phase with each other. The wave spreads and becomes weaker with distance.

A beam of photons having the same frequency, phase, and direction – that is, a beam of identical photons – is said to be **coherent**. A beam of coherent light spreads and weakens very little.

A laser is a device that produces a beam of coherent light. The atoms are excited to metastable states by an external source of energy. When most of the atoms in the medium are excited, a single photon from an atom that undergoes de-excitation can start a chain reaction. This photon strikes another atom, stimulating it into emission, and so on, producing coherent light. Most of this light is initially at random directions. Light travelling along the laser axis, however, is reflected from mirrors coated to selectively reflect light of the desired wavelength. One mirror is totalling reflecting, while the other is partially reflecting. The reflected waves reinforce each other after each round-trip reflection between the mirrors, thereby setting up a to - and - fro resonance condition wherein the light builds up to an appreciable intensity. The light that escapes through the more transparent – mirrored end makes up the laser beam.

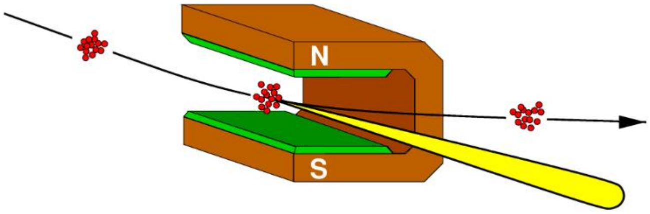
The laser is not a source of energy. It is simply a converter of energy that takes advantage of the process of stimulated emission to concentrate a certain fraction of its energy (commonly 1%) into radiant energy of a single frequency moving in a single direction, due to spatial coherence.

Synchrotron Radiation

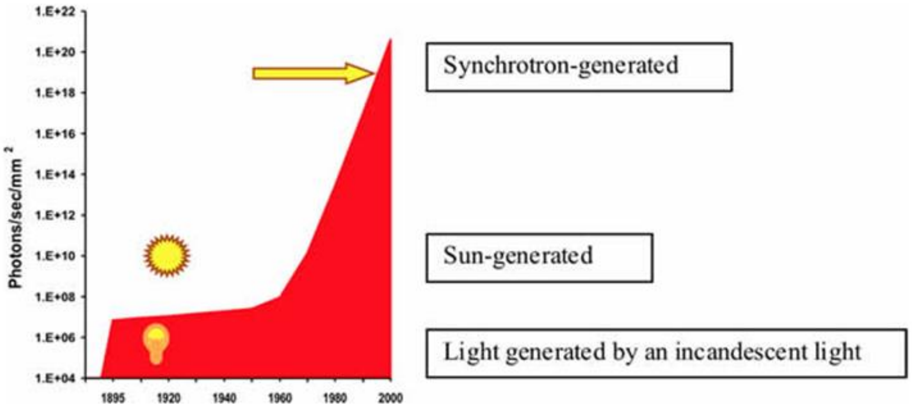
As a particle accelerates it releases energy in the form of electromagnetic radiation. This reduces the particle's energy, and thus slows the particle down: more energy is then required to accelerate it. In order to get particles up to near the speed of light this acceleration process needs to occur over a long distance. It is more convenient to bend the path around in a circle so that the particles can be accelerated round and round a loop. Because of this most particle accelerators are often circular (synchrotrons). Unfortunately, more radiation is released in this bending process.

In order to bend the electron beam it is placed in a magnetic field, the black line shows the path of the electron beam, the yellow shows that the electromagnetic radiation is emitted tangentially to the path of the electrons. The right hand slap rule can be used to determine the direction the beam will bend.

The radiation that comes off a synchrotron can be manipulated by how tight the bend is, and this radiation can be very useful for different purposes.



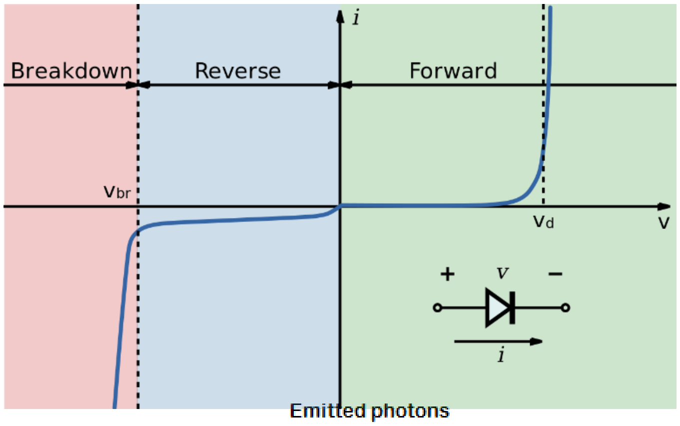
Synchrotrons can emit a broad range of electromagnetic radiation, from microwaves to X-rays, with the potential to be tuned to a required frequency. On top of this they have a high intensity or brightness, and the beam is coherent (the light waves are synchronised).



Synchrotron Light

- Is produced in the range of wavelengths (λ) from 10^{-11} (hard X-rays) to10^{-1} m (microwaves). These photons have energies respectively from 10^5 eV (hard X-rays) down to 10^{-5} eV (microwaves).
- It is of high intensity (brilliance)
- Emitted in short pulses.
- Arrives in parallel rays (collimated)
- Is coherent (all photons are in phase – wave property)
- Highly polarised (limited to a single plane for direction of wave vibration)
- Specific wavelengths can be isolated using **diffraction gratings** or **monochromators** and used for examining objects whose structural dimensions is similar to the single wavelength.
- Light is released as a very narrow cone from the bending magnets and this is then focussed to provide a very narrow beam at the work station.
- **Brightness** is a measure of how many photons per mm^2 per second there are. If the originating electron beam is widened the brightness will be less. The narrower the cone of light the greater the brightness.

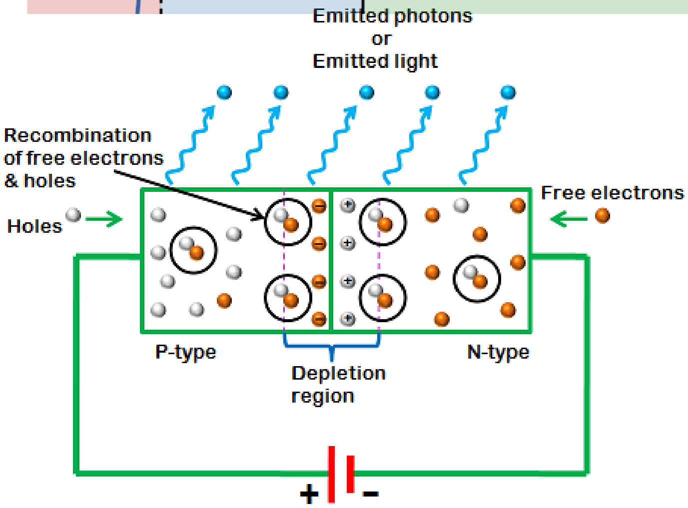
Light emitting Diodes



Light Emitting Diodes **(LED’s)** are diodes that emit light when a current passes through them at a suitable voltage. Their V-I graphs are similar to that of an ordinary diode.

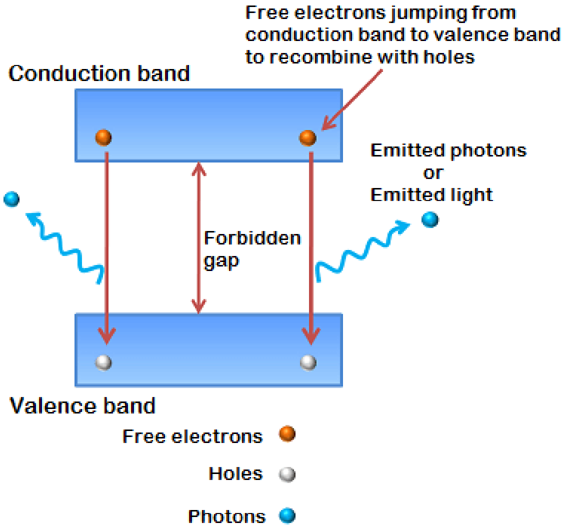
How LED’s produce light

When the p-type semiconductor is connected to the positive terminal and the n-type is connected to the negative terminal the LED is said to be forward biased. The positive terminal attracts electrons, creating more holes in the p-type semiconductor. Likewise, the holes are attracted to negative terminal, creating more free electrons in the n-types semiconductor.



The charge carriers recombine as the electrons cross from the n-region and recombine with the holes existing in the p-region. As the free electrons in the conduction band recombine with the holes in the valence band they release energy in the form of photons. This phenomenon is called electroluminescence, the emission of light from a semiconductor under an electric field. Luminescence is different to other kinds of light emission, such as incandescence, because it provides no heat.

When the valence electron leaves the parent atom, they leave an empty space in the valence shell, called a hole (a positively charged carrier). The energy level of the free electrons in the conduction band is high compared to the energy level of the holes in the valence band. Therefore, the free electrons in the conduction band need to lose energy (in the form of light) in order to recombine with the holes in the valence band.



In LEDs, the energy gap between conduction band and valence band is such that the free electrons in LEDs have greater energy than the free electrons in silicon diodes. As a result, higher energy photons are released. These high energy photons have high frequency which is visible to human eye.

The efficiency of the generation of light in the LED increases with an increase in injected current and with a decrease in temperature.

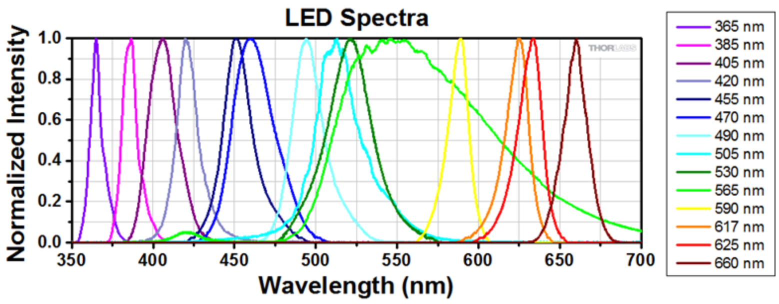
Output characteristics of an LED

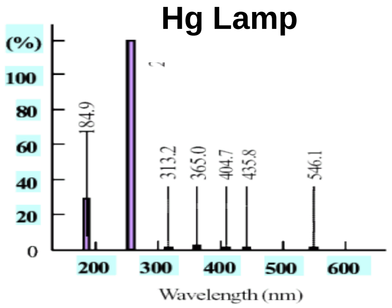
The amount of output light emitted by the LED is directly proportional to the amount of forward current flowing through the LED.

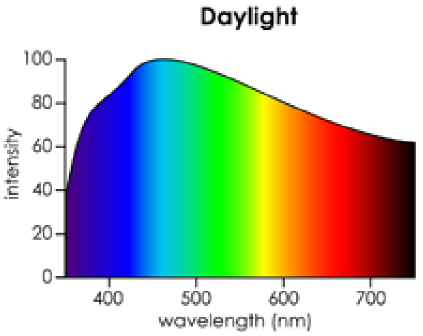
Incandescent lights

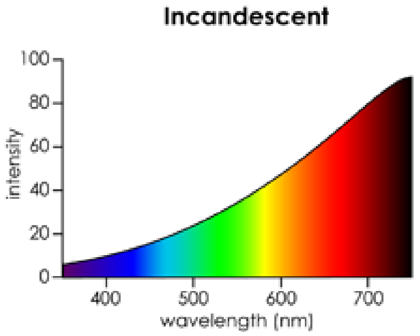
Incandescence is the term used to describe light that is produced as a result of high temperatures, it is caused by electrons bouncing around over dimensions larger than the size of the atom, emitting rdiant energy in the process. The peak frequency of radiant energy is proportional to the absolute temperature of the heated substance. Typically incandescent lights contain an infinite number of frequencies, spread across the spectrum.

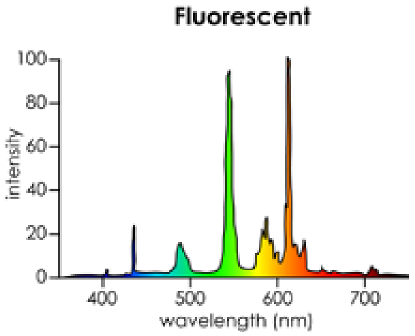
Some Common Visible Spectra











Example 5.84: 2007 Question 1 (Photonics) (3 marks)

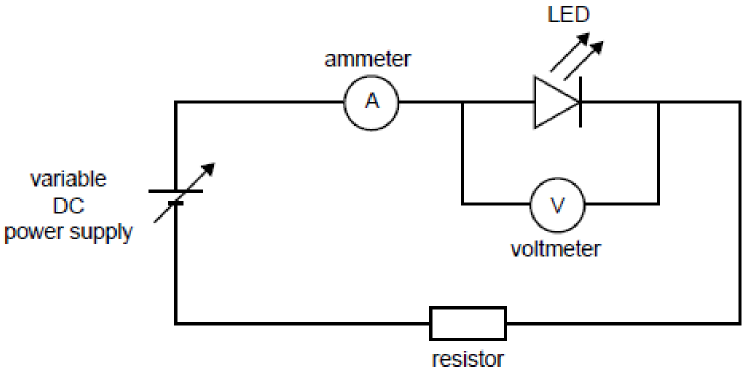
In the paragraph below, options to complete each sentence are given within the brackets. Circle the correct option in each case.

A particular laser operates by using a voltage to initially excite atoms into a higher (stable) energy state. This process is known as **[stimulated emission / population inversion / constructive interference]**.

The excited atoms are then stimulated to de-excite by emitting **[X-rays / electrons / photons]** by interacting with a photon of **[lower / the same / higher]** energy than the elevated electron energy level.

Use the following information to answer Questions 2 - 4.

Chris is testing LEDs (Light Emitting Diodes).
She has a LED which emits blue light (blue LED) and another which emits red light (red LED).
Blue light has a higher frequency than red light.
She uses the circuit shown below.



With the blue LED in the circuit the supply voltage is gradually increased. The LED does not emit light until the voltage reading on the voltmeter is 2.64 V. At this time there is a current of 5.00 mA read on the ammeter, A.

Example 5.85: 2007 Question 2 (Photonics) (2 marks)

Explain why the blue LED needs 2.64 V to emit light.

Example 5.86: 2007 Question 3 (Photonics) (3 marks)

Assuming an ideal diode, calculate the wavelength of the blue light emitted by the blue LED.

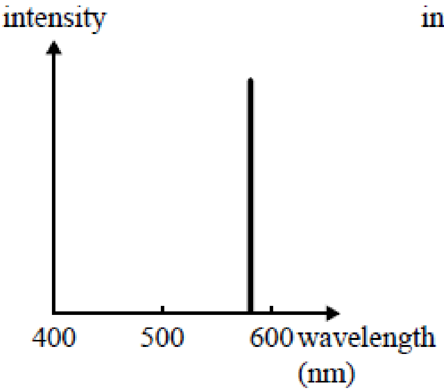
The blue LED is now replaced with the red LED. The supply voltage is left unchanged.

Example 5.87: 2007 Question 4 (Photonics) (2 marks)

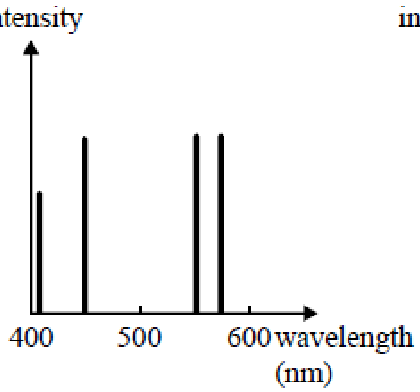
Which one of the following sets of observations **(A.D)** will now describe the situation?

	Red LED	Voltage across LED	Current through A
A.	Light emitted	Less than 2.64 V	Greater than 5.00 mA
B.	Light emitted	Greater than 2.64 V	Less than 5.00 mA
C.	No light emitted	Less than 2.64 V	Greater than 5.00 mA
D.	No light emitted	Greater than 2.64 V	Less than 5.00 mA

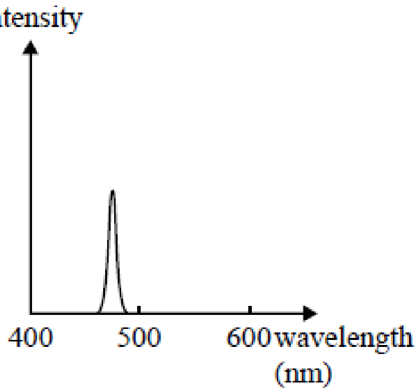
The spectra in the visible region produced by three light sources are shown in graphs 1, 2 and 3 below.



graph 1



graph 2



graph 3

The light sources are a laser, a LED and a mercury vapour lamp (not in this order).

Example 5.88: 2008 Question 1 (Photonics) (2 marks)

Which one of the following boxes correctly matches each graph with its source?

	LED	**laser**	**mercury vapour lamp**
A.	graph 1	graph 3	graph 2
B.	graph 2	graph 1	graph 3
C.	graph 3	graph 2	graph 1
D.	graph 3	graph 1	graph 2

The band gap of a LED is 1.80 eV.

Example 5.89: 2008 Question 2 (Photonics) (2 marks)

Which one of the following best gives the wavelength of light emitted by this LED?

A. 110 nm

B. 690 nm

C. 6.90×10^{-7} nm

D. 1.10×10^{-16} nm

Example 5.90: 2008 Question 3 (Photonics) (2 marks)

Comparing light from a laser and from a LED, which one of the following statements is true?

A. Light from a LED is coherent but light from a laser is incoherent.

B. Light from both a LED and a laser is coherent.

C. Light from a laser has a narrow range of wavelengths (more monochromatic) than light from a LED.

D. Light from a LED is pulsed but light from a laser is continuous.

Example 5.91: 2008 Question 4 (Photonics) (2 marks)

Which one of the following statements best describes stimulated emission in a laser?

A. Atoms are raised to a metastable state.

B. A population inversion is created.

C. Photons interact with atoms in a metastable state causing them to release their energy as photons.

D. Photons interact with the atoms in a metastable state to cause emission of electrons.