Antonine Physics AS

Topic 3 Quantum Physics

How to Use this Book

How to use these pages:

- This book intended to complement the work you do with a teacher, not to replace the teacher.
- Read the book along with your notes.
- If you get stuck, ask your teacher for help.
- The best way to succeed in Physics is to practise the questions.

There are many other resources available to help you to progress:

- Web-based resources, many of which are free.
- Your friends on your course.
- Your teacher.
- Books in the library.

This is an electronic book which you can download. You can carry it in a portable drive and access it from your school's computers (if allowed) as well as your own at home.

Quantum Physics explains many things that Classical Physics cannot. The photoelectric effect did that to Physics one hundred years ago; light was a wave and that was that. Or was it?

Many everyday electronic devices depend on quantum physics, e.g. charge-coupled devices in a digital camera, or the light emitting diode.

We will explore the photoelectric effect and the photon model of light. We will consider the energy ladder that ensures that photons of a particular energy are observed when atoms are excited. This leads to unique spectra being observed, which give rise to the fingerprints of particular elements.

We will also explore the LASER and its associated phenomena of force from photons and photon pressure. These last two tutorials are intended for 2nd Year students of the Welsh Board and the CEA Board.

Quantum Physics continues to capture the imagination.

Topic 3 Quantum Physics	
Tutorial 3.01 Evidence for Light as a Photon	
All Syllabi	
Contents	
3.011 Simple Demonstration	3.012 Photon Model
3.013 Electron-volt	

3.011 Simple Demonstration

The concept of **wave-particle duality** was the start of modern physics in the middle to late Nineteenth Century.

We can show the **photoelectric effect** with apparatus like this (*Figure 1*).

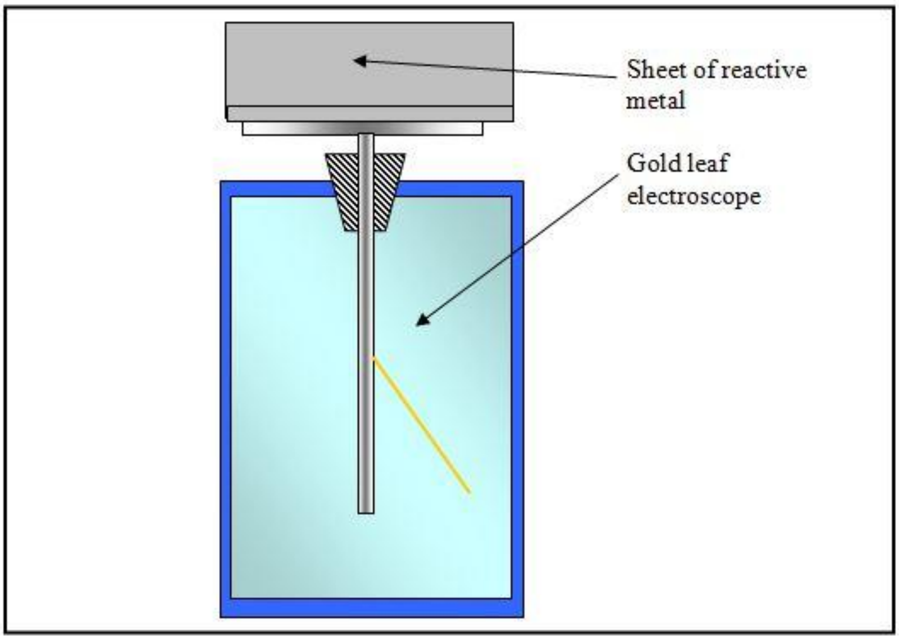


Figure 1 Showing the photoelectric effect.

We do the experiment like this:

1. We charge the electroscope with a negative charge.
2. We expose the reactive metal to light of a long wavelength, e.g. red.
3. We observe that there is no effect, however bright the light.
4. We then expose the metal to short wavelength light, e.g. UV.
5. This time we see that the gold leaf drops down, showing that the electroscope is losing charge.

6. It does not matter how bright or dim the UV light is.

7. No effect is observed when the electroscope is positively charged.

If different reactive metals are used, the following results are observed:

Metal	***X-rays***	***Ultra-Violet***	***Blue Light***	***Red Light***
Magnesium	Yes	No	No	No
Zinc	Yes	Yes	No	No
Sodium	Yes	Yes	Yes	No
Caesium	Yes	Yes	Yes	Yes

This led to the conclusion that:

- Electrons were being knocked off. Reactive metals have outer shell electrons that can be removed easily.
- Red light would not show this effect however bright it was. So the amplitude of the light wave was not important. Red light only worked for caesium, which is a very reactive metal.
- There was a **threshold frequency** at which this phenomenon started to occur. Light waves with a frequency higher than this (shorter wavelength) always showed the effect, whatever the brightness; light waves with a lower frequency never showed it.
- The more reactive the metal, the lower was the threshold frequency.
- This indicated particle behaviour in light.

These findings led to the notion of light being tiny little packets of wave energy called **photons**.

If light were a wave, we would see electrons being knocked off by very bright red light. Dim violet light would not remove a photoelectron.

3.012 Photon Model

Further work by Max Planck in 1900 produced the **Photon Model of Electromagnetic Radiation**. We can sum this up in the following points:

- Light and other electromagnetic radiation is emitted in bursts of energy. We say that it is **quantised**.
- The packets of energy, **photons**, travel in straight lines.
- When an atom emits a photon its energy changes by an amount **equal** to the photon energy.
- The energy changes are discrete amounts or **quanta** (a Latin word meaning "how much".)

The frequency of the light and the energy are related by a simple equation:

$$E = hf \ldots\ldots\, \textit{Equation 1}$$

[E – energy in J; h – Planck's Constant; f – frequency of the radiation in Hz]

The constant h is Planck's constant with the value 6.6×10^{-34} Js (**joule seconds**, NOT joules per second).

We can combine Equation 1 above with the wave equation (*Equation 2*):

$$c = f\lambda \ldots\ldots\, \textit{Equation 2}$$

These gives us:

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

Wavelengths of light are often measured in nanometres (nm) where 1 nm = 1×10^{-9} m. For example, 635 nm = 635×10^{-9} m.

3.013 Electron-volt

The **joule** is the SI unit for energy. However atomic physicists find the joule far too big and clumsy. (You would not measure the width of your desk in kilometres.) So, they use a unit called the **electron volt** (eV).

The electron volt is the amount of energy used when a charge of electronic charge passes through a potential difference of 1 volt.

The charge on an electron is 1.6×10^{-19} C, so **1 eV = 1.6×10^{-19}** J.

Electron volts are almost always used in atomic and nuclear physics, but before using equations like $E = hf$, the energies MUST be converted to joules. We do this by **multiplying** by **1.6×10^{-19} J**.

To convert joules to electron volts we **divide** by **1.6×10^{-19}** J.

Tutorial 3.01 Questions

3.01.1

Why do these results suggest that light is not a wave?

3.01.2

What is the photon energy of light wavelength 350 nm?

3.01.3

Convert the answer to Question 2 to electron volts.

3.01.4

A photon has energy of 10.3 eV. What is its wavelength? Where on the electromagnetic spectrum would this be?

Tutorial 3.02 The Photoelectric Effect	
All Syllabi	
Contents	
3.021 Photons and Quantum Physics	3.022 Photoelectric Emission
3.023 Threshold Frequency	3.024 A Simple Model
3.025 Einstein's Photoelectric Equation	

3.021 Photons and Quantum Physics

Albert Einstein developed the theory further to study how atoms interacted with photons. He produced the notion of **quantum** physics, in which electromagnetic radiation has a particulate nature. The essential points of quantum theory are:

- All electromagnetic radiation is emitted in tiny bursts of energy called photons
- Photons travel in one direction only and in a straight line
- When an atom emits a photon its energy changes by the energy of the photon.
- Energy contained in a photon is given by $E = hf$.

Detailed study called for more sophisticated experiments that used apparatus as in *Figure 2*.

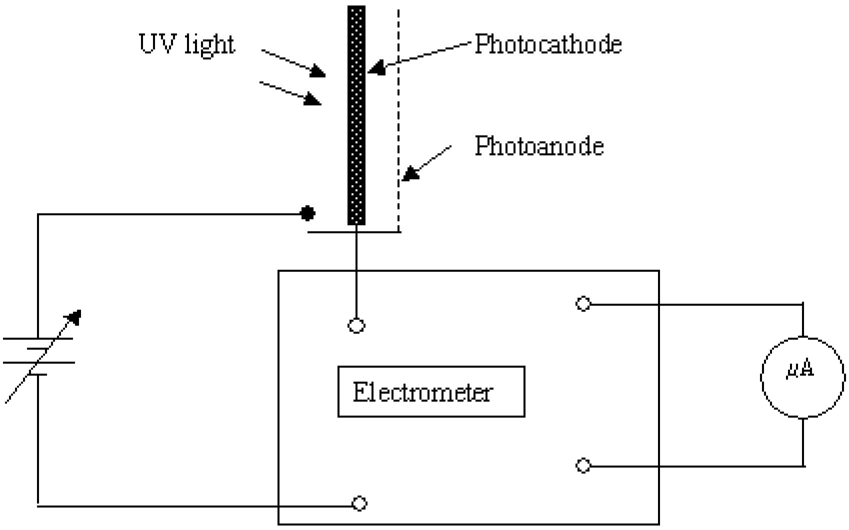


Figure 2 More detailed measurement of the photoelectric effect.

Details of this experiment are NOT needed for the AQA exam. However, to understand the results, we need to be aware of what goes on in the experiment:

- The photocathode is given a <u>positive</u> voltage, and the photo-anode a <u>negative</u> voltage.
- This means that **photoelectrons** (electrons released by interaction with a photon. One photon releases one electron) are <u>repelled</u> from the anode.
- If the electrons have lots of kinetic energy, they can overcome the repulsive force.

We turn up the reverse voltage until the electrons with the most kinetic energy are just repelled. The voltage is called the **stopping voltage**. We can see what is happening in this diagram *(Figure 3*):

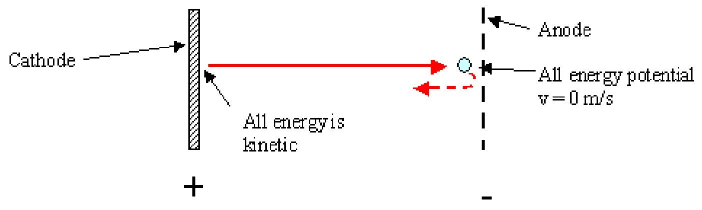


Figure 3 The stopping voltage

The totally unexpected result is that the **maximum kinetic energy** of the photoelectrons is **exactly the same** <u>regardless</u> of the intensity of the illumination. However dim or bright the light, the maximum kinetic energy is the same.

How can we explain these observations? Look at the diagram (*Figure 4*).

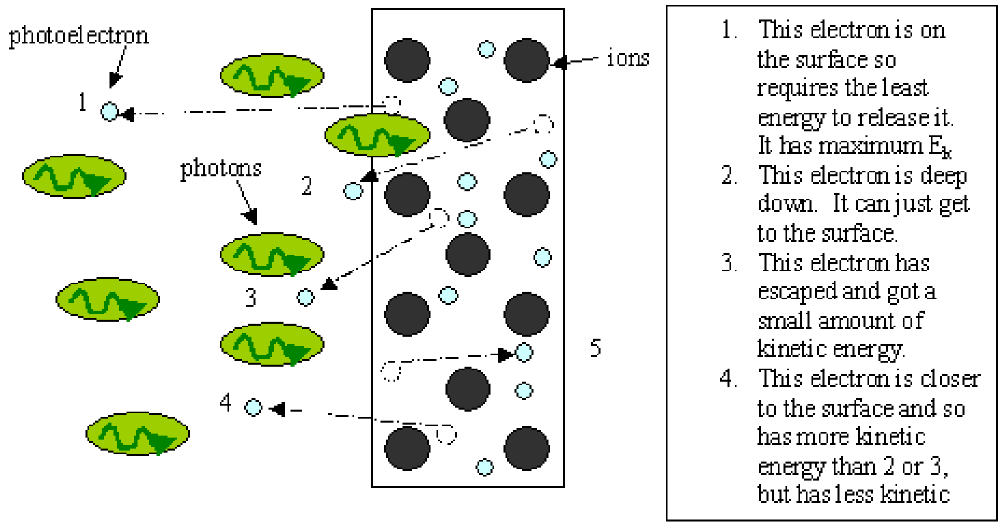


Figure 4 Explaining the stopping voltage

It is important to understand that **each photon can eject only one photoelectron**. So, if we can count the number of photoelectrons, we know the number of photons.

Although Figure 4 is a simplification as to what really happens, we can see that the photoelectrons are released with a **range** of kinetic energies. The lowest kinetic energy is where the electron just manages to crawl out. It will be hauled back pretty quickly by the electrostatic forces.

A **vacuum photocell** works in a similar way. The photocathode is made of a reactive metal and placed in a glass capsule that has a high vacuum in it. Therefore, the reactive metal does not tarnish by reacting with the oxygen in the air. *Figure 5* shows the idea.

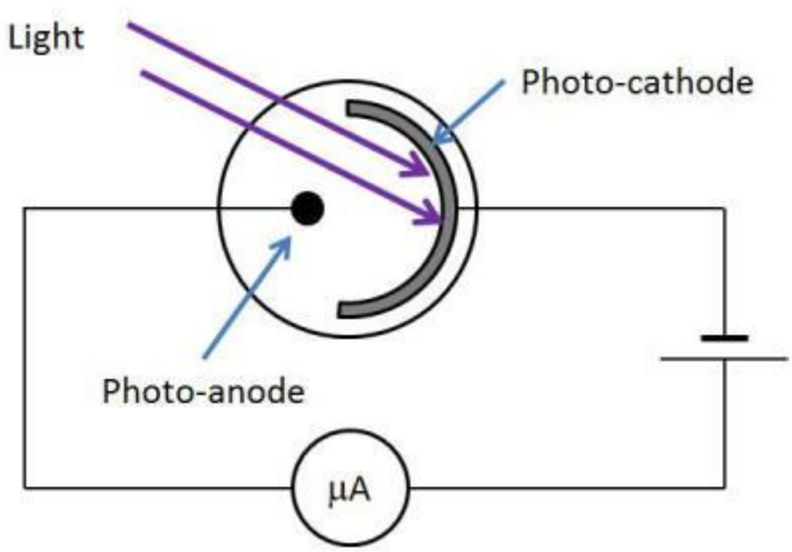


Figure 5 A vacuum photocell

The light removes **photoelectrons** from the **photocathode**. The electrons move to the **photo-anode**. The **photo-current** depends on the **intensity** of the light - one photon releases one photoelectron. The more photons (above the threshold frequency) per second, the more photoelectrons are released each second. So, the photo-current increases.

If the photo-anode is made negative, the emitted photoelectrons are slowed down. If the reverse voltage is the same as the work function of the metal, the current falls to zero in the same way as we saw above.

A photocell is used as a **light detector** in a film projector in a cinema when they project traditional chemical films. The sound track is etched onto the film as in *Figure 6*.

Figure 6 Sound track on an old-fashioned cinema film

The sound track passes a light source above a photocell. The soundtrack width varies as it is **modulated** according to the speech and other sounds on the film. The wider the track, the more photoelectrons are released as more light gets through. Therefore, there is a bigger photocurrent. The photocell is connected in series with a resistor, and the varying voltage resulting from the varying current is amplified to be played through a speaker.

3.022 Photoelectric Emission

We can summarise these findings in three rules, the **laws of photoelectric emission**.

1. The number of electrons emitted per second depends on the intensity of the radiation.

2. The photoelectrons have a range of energy, from zero to a maximum value. The maximum value is determined by the frequency of the radiation, not the intensity.

3. A minimum value for the frequency is needed, the **threshold frequency**.

The maximum kinetic energy **has the same value in eV as the stopping voltage**. A voltage of **5 volts** gives rise to an electron energy of **5 eV**. This stands to reason. We know that energy = charge × voltage, and that the electron carries a single electronic charge ($1e = 1.6 \times 10^{-19}$ C).

So, if that charge moves through a potential difference of 5 V, the work is done is 5 eV or 8.0×10^{-19} J.

3.023 Threshold Frequency

The graph (*Figure 7*) shows how the energy of the photoelectrons depends on the frequency (colour) of the light:

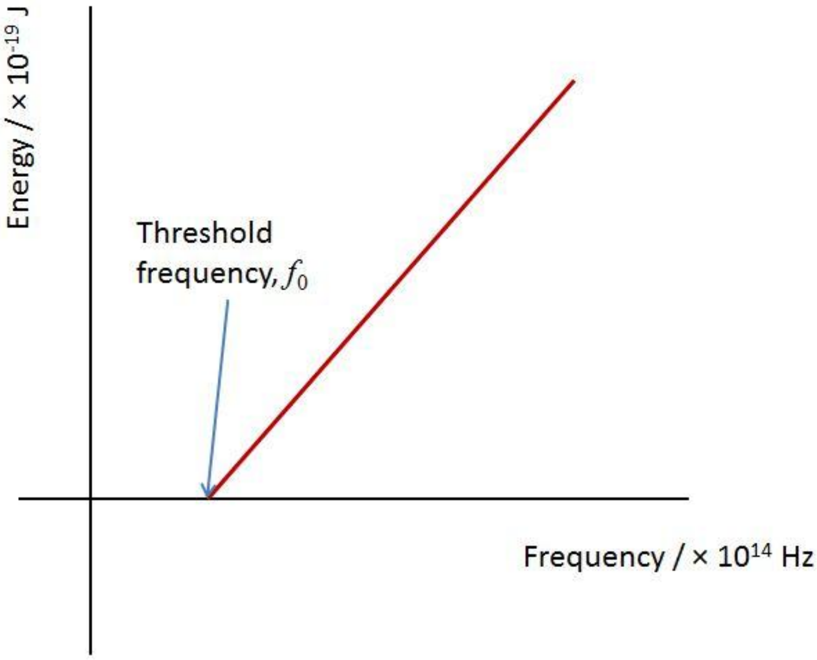


Figure 7 Graph showing the threshold frequency for photoelectron emission

There has to be a **threshold frequency** below which no photoelectrons are emitted, **regardless of brightness**. Therefore, radio waves, however strong, will NEVER affect photographic film; weak gamma rays will.

Worked Example
What is the threshold frequency of a metal whose photoelectrons are stopped by a stopping voltage of 5.6 V?
Answer The maximum kinetic energy is 5.6 eV = 5.6 × 1.6 × 10^{-19} = 8.96 × 10^{-19} J This gives us a photon energy of 8.96 × 10^{-19} J 8.96 × 10^{-19} J = 6.6 × 10^{-34} Js × f f = 8.96 × 10^{-19} J ÷ 6.6 × 10^{-34} Js = **1.36 × 10^{15} Hz**

Worked Example What wavelength is this?
Answer Use the wave equation $c = f\lambda$ λ = 3 × 10^8 m/s ÷ 1.36 × 10^{15} Hz = **2.20 × 10^{-7} m** = 220 nm

Physicists tend to use **nanometres** to measure wavelength of light, so red light has a wavelength of 600 nm. 600 nm = 600 × 10^{-9} = 6 × 10^{-7} m.

Failure to convert correctly from nanometres to metres is a common bear trap.

Useful Data

Mass of an electron = 9.11 × 10^{-31} kg

Speed of light = 3 × 10^8 m/s

Planck's Constant = 6.63 × 10^{-34} Js

When you answer this kind of question, you need to be very careful about what you say when discussing wavelengths. A photon with a long wavelength carries less energy than one with a short wavelength. So, if the wavelength of a photon is longer than the wavelength suggested by the threshold frequency, photoelectrons will not be ejected.

Confusion here is a very common bear trap.

3.024 A Simple Model

We can use a **model** to explain this. Consider a rugby player about to take a place kick (*Figure 8*). (I was hopeless at rugby and any other ball game. I learned that there were fairies on the rugby pitch - "Get in there ya fairy!")

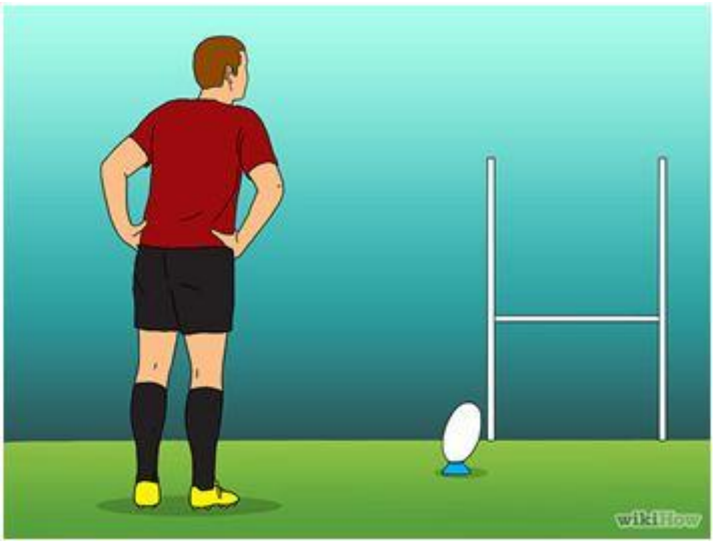


Figure 8 Simple model to explain the threshold frequency (Image from WikiHow).

The ball is mounted on a small stand. In the past, the player would remove a small divot from the surface of the pitch with his heel. I presume that this would not exactly please the ground staff.

- If the kicker kicks the ball with too little energy, it will stay where it is.
- If he kicks the ball with just enough energy, the ball will roll off the stand.
- If there is more than enough energy, the ball will fly off (over the bar?).

3.025 Einstein's Photoelectric Equation

This is sometimes called **Einstein's Photoelectric Law**. Here are some useful data.

Useful Data

Mass of an electron = 9.11×10^{-31} kg

Speed of light = 3×10^{8} m/s

Planck's Constant = 6.63×10^{-34} Js

Summing up what we have learned already:

- When photoelectrons are removed from a metal surface, a certain amount of work has to be done in removing them.
- The photoelectrons will lose some of their kinetic energy in order to escape the attractive field of the positively charged ions.
- The work required to remove the photoelectron is called the **work function**.
- It is given the physics code ϕ (phi - a Greek letter 'f') and is measured in joules, or electron volts. Sometimes, depending on the syllabus or text book, the code is written as a capital Phi, Φ.

Work function is a property of the metal. The more reactive the metal, the lower the value of the work function. This can be seen in this graph (*Figure 9*).

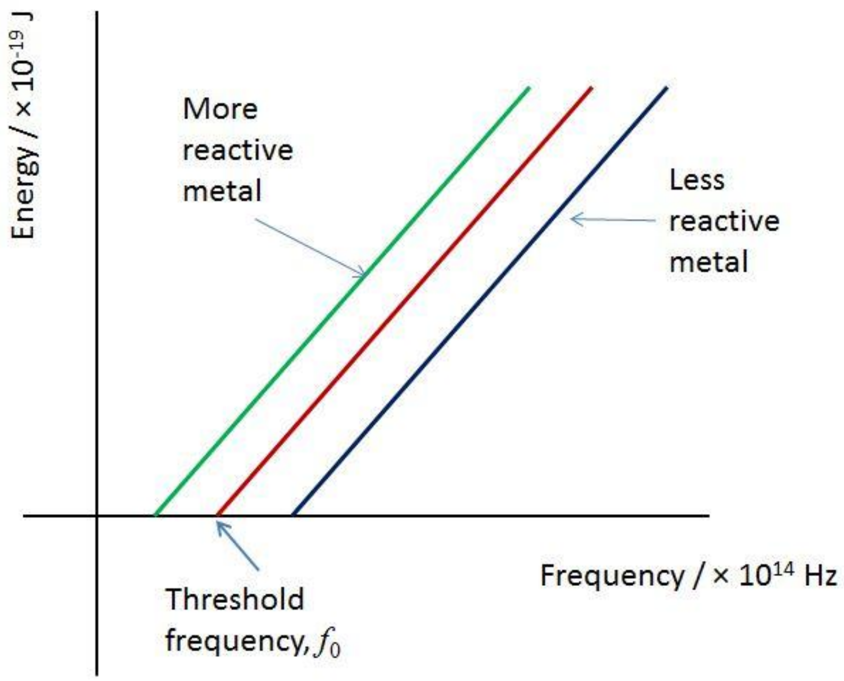


Figure 9 Graph showing the work functions of more and less reactive metals

We find that the **gradient** of this graph is **constant**, <u>regardless</u> of the metal. This is important.

It is tempting to relate the work function to the molar ionisation energy. If you convert the work function to kilojoules per mole, you will find that it is somewhat lower than the ionisation energy per mole. This is because the ionisation energy in chemistry is worked out using metals that have been turned into gases. The photoelectric effect involves solid metals which have free electrons which are more easily removed.

The energy received from a photon is split into:

- The work necessary to separate the electron from the metal (the work function).
- The kinetic energy.

This is illustrated in the diagram below (*Figure 10*)

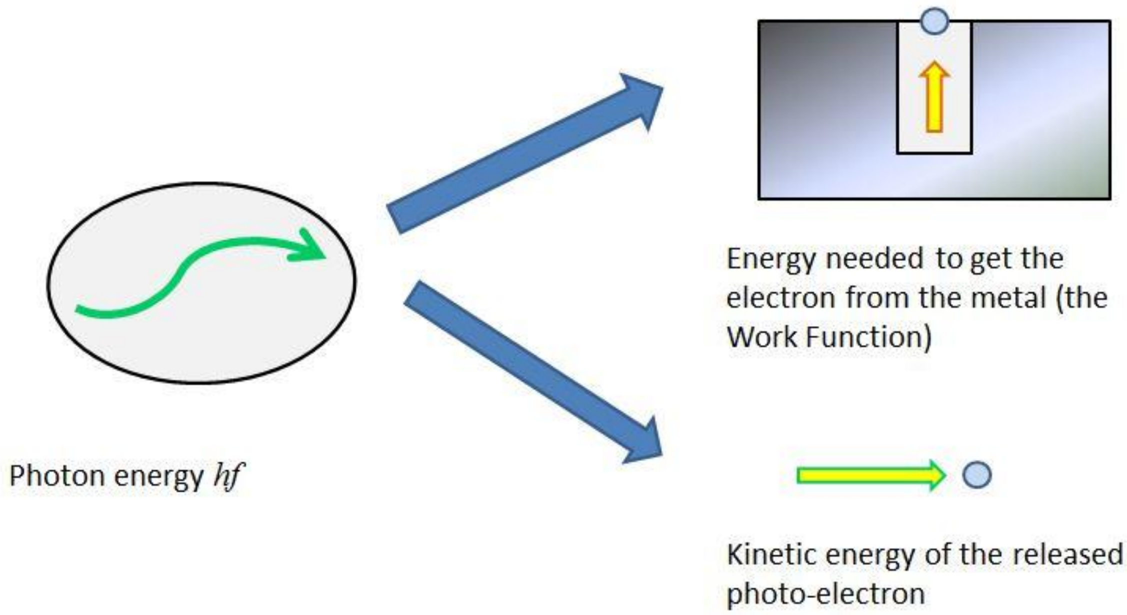


Figure 10 How the photon energy is split.

Energy of Photon = work done to remove electron + kinetic energy of the electron

In code:

$$E = \phi + E_k \text{ ....Equation 3}$$

$$E = \phi + 1/2\, mv^2 \text{ ....Equation 4}$$

We must note the following:

- E_k is the **maximum kinetic energy** (the charge × stopping voltage), i.e. the kinetic energy of the fastest electrons. We are not interested in slower electrons.
- The maximum kinetic energy is dependent only on the frequency, NOT the intensity. A more intense beam produces more photons per second, but each photon has the same energy.

We can work out the work function of any metal by plotting the maximum energy against the frequency (*Figure 11*).

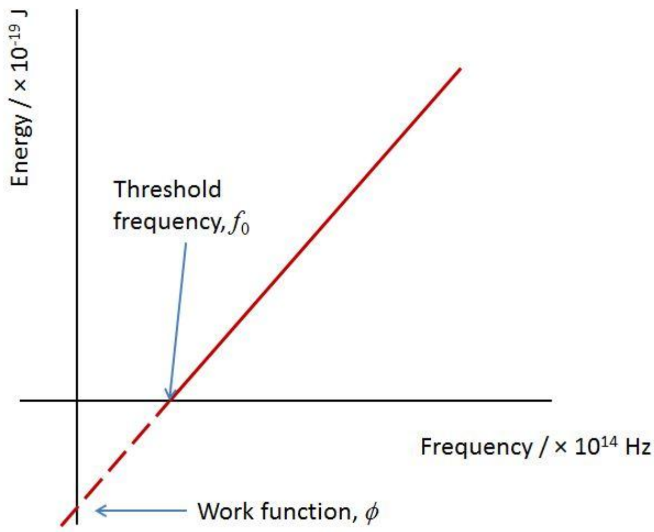


Figure 11 Extrapolating the energy-frequency graph to work out the work function.

We find that the **gradient** of this graph is **constant**, regardless of the metal. The equation of the graph is:

$$E_k = hf - \phi \text{ ....} \textit{Equation 5}$$

It fits in with the general equation for a straight-line graph.

$$y = mx + c \text{ .... } \textit{Equation 6}$$

So, the gradient is Planck's constant, h. The intercept is negative, $-\phi$.

The work function can be worked out from the threshold frequency, ϕ_0. At the threshold frequency, $E_k = 0$. Therefore:

$$0 = hf_0 - \phi \text{ .... } \textit{Equation 7}$$

$$\phi = hf_0 \text{ .... } \textit{Equation 8}$$

Therefore, we can rearrange:

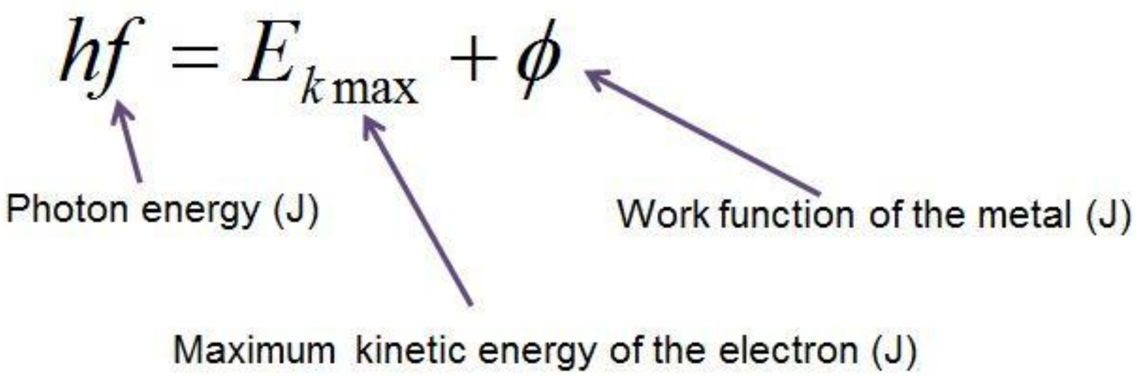
$$f_0 = \frac{\phi}{h}$$

.... *Equation 9*

Where:

- f_0 – threshold frequency (Hz)
- ϕ – work function (J)
- h – Planck's Constant (J s)

The Photoelectric Effect Equation is usually written like this. It is a rearrangement of Equation 5.



Worked Example

A metal surface has a work function of 3.0 eV and is illuminated with radiation of wavelength 350 nm. Work out:

(a) The maximum wavelength that causes photoelectric emission.

(b) The maximum kinetic energy of the photoelectrons.

(c) The speed of the photoelectrons.

Answer

(a) Work out the work function in joules:

$\phi = 3.0 \text{ eV} \times 1.6 \times 10^{-19} \text{ J eV}^{-1} = \mathbf{4.8 \times 10^{-19} \text{ J}}$.

Now work out the frequency that this corresponds to. The minimum frequency is the frequency at which a photon will just release an electron. Therefore, we use the equation $E = hf_0$ where f_0 is the threshold frequency. Since the energy given by the photon is the work function ϕ, we can rewrite the equation as $\phi = hf_0$.

Rearranging:

$f_0 = \phi/h = 4.8 \times 10^{-19} \text{ J} \div 6.63 \times 10^{-34} \text{ J s} = \mathbf{7.24 \times 10^{14} \text{ Hz}}$

Use the wave equation to work out the wavelength:

$\lambda = c/f = 3.0 \times 10^{8} \text{ m s}^{-1} \div 7.25 \times 10^{14} \text{ Hz} = 4.14 \times 10^{-7} \text{ m} = \mathbf{414 \text{ nm}}$

(b) Use $E_{max} = hf - \phi$

First work out the frequency of the 350 nm light:

$f = c/\lambda = 3.0 \times 10^{8} \text{ m s}^{-1}$ ¸ $350 \times 10^{-9} \text{ m} = 8.57 \times 10^{14} \text{ Hz}$

Now put this into the photoelectric equation:

$E_{max} = hf - \phi = (6.63 \times 10^{-34} \text{ J s} \times 8.57 \times 10^{14} \text{ Hz}) - 4.8 \times 10^{-19} \text{ J} = \mathbf{8.82 \times 10^{-20} \text{ J}}$

This is equivalent to **0.55 eV**. It is perfectly acceptable to express your answers in eV or joules.

(c) Now we use the kinetic energy of the electron to find out its speed:

Mass of an electron = 9.11×10^{-31} kg

$v^2 = 2E_k/m = 2 \times 8.82 \times 10^{-20}$ J $\div 9.11 \times 10^{-31}$ kg $= 1.94 \times 10^{11}$ m^2 s^{-2}

→ $v = \sqrt{}\,(1.94 \times 10^{11}$ m^2 s^{-2}) = **4.40×10^5 m s^{-1}** (= 4.4×10^5 m s^{-1} to 2 significant figures)

Even these low energy electrons move like greased lightning.

Tutorial 3.02 Questions

3.02.1

Which one of the photoelectrons has the most kinetic energy? Why?

3.02.2

Which one of the photoelectrons in *Figure 4* has the least kinetic energy? Why?

3.02.3

If the stopping voltage for a photoelectron is 3 V, what is the kinetic energy in eV and joules?

3.02.4

A metal gives out photoelectrons that have a stopping voltage of 2.6 V. Will light of wavelength 615 nm cause photoelectrons to be ejected?

3.02.5

(a) The Work Function of potassium is 3.52×10^{-19} J. What is meant by this statement?

(b) When radiation of a suitable frequency falls on a potassium surface, photoelectrons are emitted. What is the minimum frequency at which this can occur?

(c) What is the maximum speed of the photoelectrons emitted when radiation of 400 nm falls on the potassium surface?

Useful Data

Mass of an electron = 9.11×10^{-31} kg

Speed of light = 3×10^{8} m/s

Planck's Constant = 6.63×10^{-34} Js

Tutorial 3.03 Ionisation and Excitation of Atoms	
All Syllabi	
Contents	

3.031 Ionisation

When we heat a gas or pass an electric current through it, we can make it glow. We have **ionised** the gas. Ionisation is due to **collisions** with the outer shell electrons from other electrons. One or more of the outer electrons are removed. This can happen due to collisions with an electron or a high energy photon. An electron is removed if the collision energy is **greater** than the ionisation energy. Once the electron is removed, any left-over energy is **kinetic**. *Figure 12* shows the idea.

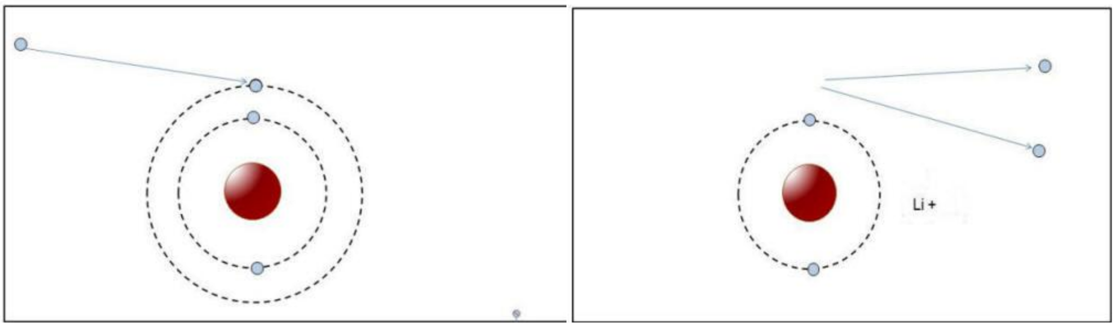


Figure 12 Ionisation of a lithium atom by electron collision

In this case, the electron has knocked off an outer shell electron of this lithium atom, leaving a lithium 1+ ion (carrying a charge of $+1.6 \times 10^{-19}$ C). If we put enough energy in, we could remove all the electrons.

- The electron must have at least the same kinetic energy as the ionisation energy of the atom.
- The electron that has been removed from the atom will have a certain amount of kinetic energy.
- The atom will gain a positive charge and will be attracted to a negative electrode.
- The positive ion will attract an electron.

A **plasma** is a **gas** where some of the atoms or molecules have had their electrons removed, i.e., the atoms or molecules have been **ionised**. They therefore consist of **ions**, **electrons** and **neutral** particles. It is not necessary to remove all the electrons, though. Indeed, to get total ionisation require insanely high temperatures. The properties of a plasma are:

- Electrically **conductive** due to the presence of both positively charged and negatively charged particles. Unionised gases do not conduct electricity.
- Strongly **influenced** by electric and magnetic fields.

Physicists often describe plasmas as the **fourth state of matter**, after solids, liquids and gases.

The gas is charged, and a current flows. Plasmas are often very hot.

- Ionised gases can form plasma.
- Cold plasmas happen when a small proportion of the atoms are ionised.
- Cold plasmas are hot to us, several thousand K.
- A hot plasma has most of the atoms ionised. Some atoms may have all the electrons removed.

Plasmas are formed by intense heating, or by intense electromagnetic fields. In nature plasmas are found in the coronas of stars, which are intensely hot. In lightning, plasmas are formed in the intense electromagnetic fields. In technology, plasmas are found in fluorescent light fittings, discharge tubes and plasma TV screens

Figure 13 shows a **discharge tube**:

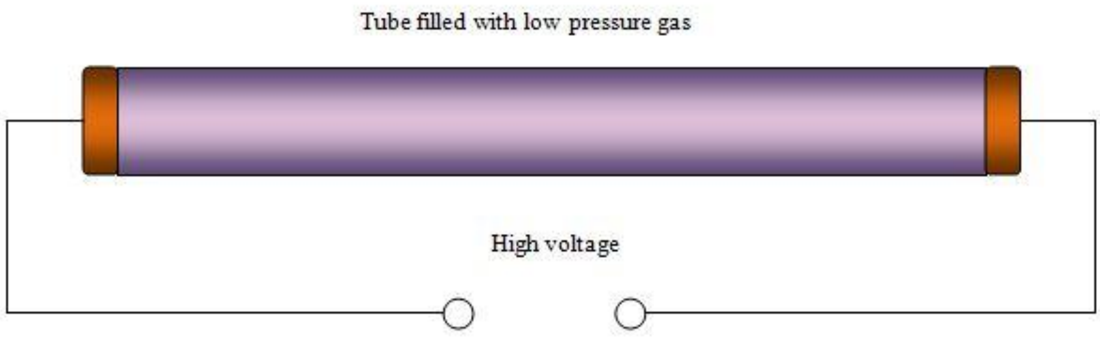


Figure 13 An ionised gas glows.

The ionised gas glows dimly. The brightness depends on the current. The more electrons knocked off, the bigger the current. A positive ion is clearly very attractive to other electrons. The attraction will occur rapidly through the **electromagnetic** force.

3.032 Emission Spectra

If we look at the glowing gas through a **spectrometer**, we see the **spectrum** of the gas which is distinctive for that gas. Unlike the spectrum of the Sun, in which we see all the colours of the rainbow, we only see certain colours, while others are absent. We call this kind of spectrum a **line emission spectrum**. The colours are discrete wavelengths (*Figure 14*).

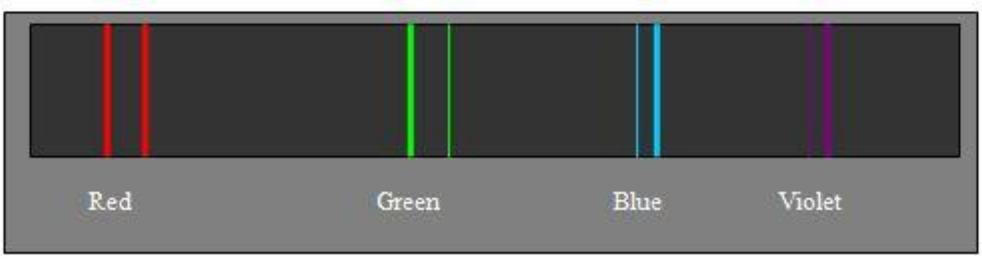


Figure 14 A typical emission spectrum

All elements have a **unique** emission spectrum, like a fingerprint. We can predict what wavelengths are emitted from a particular element, but this is beyond what we need to know at this level

When a gas is ionised, one or more outer electrons are ripped off. The molecule has become positive. It will recombine with an electron and lose energy, giving that energy back in the form of a **photon**. Other atoms may not have been ionised but are still in a very excited state. The atoms have interacted with the photon and the electrons have moved to a **higher energy level**.

About a microsecond later, the electrons lose their energy as a **photon** and return to the stable state, called the **ground state**. The important thing to remember is that electrons can only exist at **permitted energy levels**. It's like a person standing on a ladder; he can stand at one rung up, two rungs, *etc*., but NOT at a height of 1.5 rungs.

As we consider energy levels in atoms, we will look at **hydrogen** which fits this model well. (Hydrogen has one electron.) More complex atoms with several electrons do not.

3.033 Absorption Spectra

If we drop sodium chloride crystals into a Bunsen flame, we see an orange flame. If we do this while shining a sodium light onto the flame, we see a shadow (*Figure 15*).

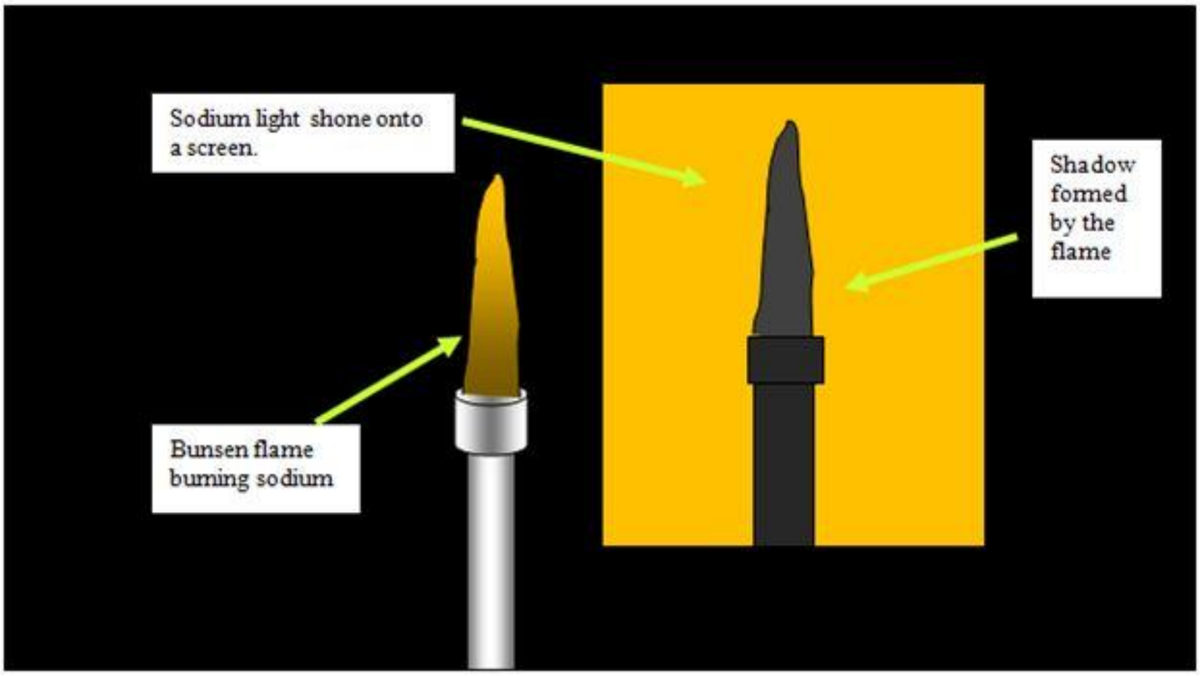


Figure 15 Showing absorption in a Bunsen flame.

This is because Sodium light is, to all intents and purposes, **monochromatic**[1], meaning that the emission spectrum is of a **single** frequency, as shown by a single colour. When sodium chloride is dropped into the Bunsen flame, it ionises, which gives off the distinctive yellow light. The photons in the flame are scattered in all directions, reducing the intensity of the sodium light.

We call this an **absorption** spectrum.

As with emission spectra, the **absorption** spectrum of a given element is **unique**. It is the signature of the particular element.

[1] Sodium light is, strictly speaking, not monochromatic. There are two very close wavelengths, 589.0 nm and 589.6 nm, but these are very difficult to separate. In the normal Physics lab, we can state that sodium light is monochromatic.

In an **absorption spectrum**, we shine the whole spectrum of visible light through the glowing gas. We see black lines. This is because the photons emitted in the gas are scattered in all direction. The light is much dimmer, giving the impression of a shadow (*Figure 16*).

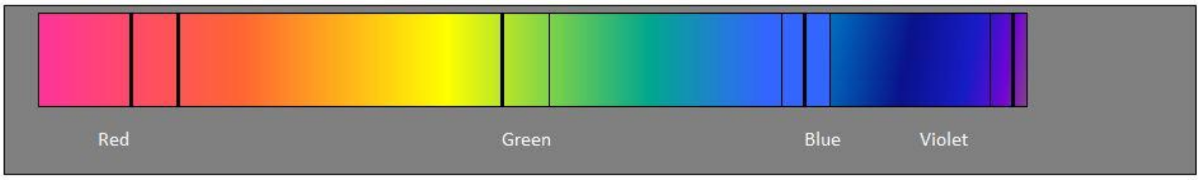


Figure 16 A simple absorption spectrum

Gases in stars are analysed in this way. Each gas has a distinctive and unique pattern of **spectral lines**. Each line represents an **energy level**, which can be thought of as a rung on the energy ladder. We will look at this next.

3.034 Excitation

Atoms can interact with photons of <u>lower</u> energy than is required to remove electrons from them. The photons we looked at in the photoelectric effect could remove the electrons from very reactive metals like caesium. Photons can interact with other atoms to give them extra energy, which makes them **excited**. But the electron is NOT removed. This is illustrated in *Figure 17*.

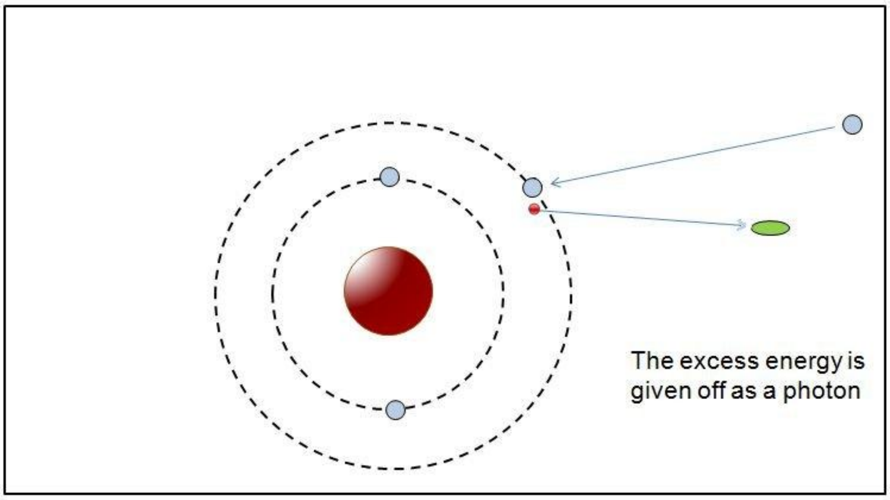


Figure 17 Excitation of an atom leads to photon emission

Excited atoms have very particular **energy levels** to which the electron rises. The incoming electron has to have <u>exactly</u> the right amount of energy to raise the electron to a higher energy level. If it does, the electron is raised to the new energy level. Almost immediately the electron falls back to its ground state, emitting a photon.

If the incoming electron does not have the right energy, there is no excitation. No photon is emitted.

Photons can also excite electrons to higher energy levels. Again, they have to have exactly the right energy. If they do, they are absorbed, and a photon of the same wavelength is emitted. If not, they are not absorbed at all.

If we look at a spectrum of hydrogen, we find lines at several discrete wavelengths.

Each line represents the energy of a photon as the electron makes a **transition** from a higher energy level to a lower level. This we can show in *Figure 18*.

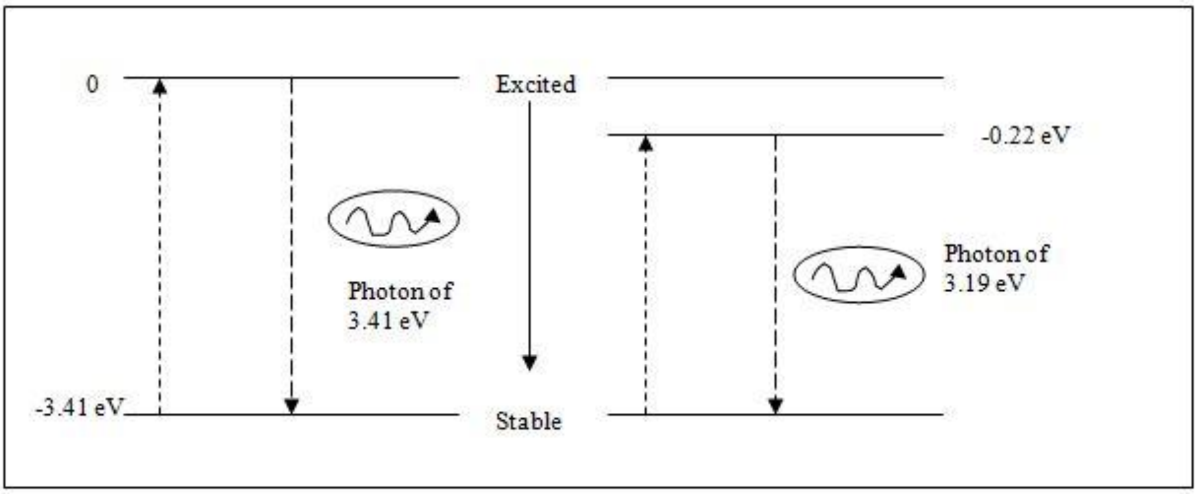


Figure 18 Electron falling between energy levels to emit photons of specific energies.

The electron does a job of work in releasing a photon; it has lost potential energy. Therefore, we start at the **highest** level which we give a value of **zero**. Therefore, the electron falls from the zero point to the –3.41 eV level. Notice that it can do this in three possible leaps or transitions. One is straight from 0 to -3.41 eV. The other is from 0 to -0.22 eV and -0.22 eV to -3.41 eV. These transitions result in photons of 0.22 eV, 3.19 eV and 3.41 eV. We would see these as coloured lines.

Tutorial 3.03 Questions

3.03.1

Describe how an atom becomes ionised.

3.03.2

Explain what happens when an electron interacts with an ionised atom.

3.03.3

In a spectrum of an ionised gas, only certain coloured lines can be seen. Why does this happen?

3.03.4

What is the difference between an ionised and excited atom?

Tutorial 3.04 Energy Levels in Atoms	
All Syllabi	
Contents	
3.041 Key Words	3.042 Excited atoms
3.043 Energy Levels in Atoms	3.044 Ionisation and excitation

3.041 Key Words

You will come across these key words in the **bold** type:

- **Electrons** make a **transition** from a higher energy level to a lower.
- **Photons** are given out that have the same energy as the transition energy.
- The **highest energy level** is where **ionisation** occurs.
- The **lowest level** is the **ground state**.

3.042 Excited atoms

In **excitation**, a photon or electron interacts with an electron in the electron shells. The electron is raised to a higher energy level but is NOT removed. It rises to a **higher energy level**.

We will consider a hydrogen atom being excited by photons. Hydrogen is the simplest atom. Consider a photon being absorbed by a hydrogen atom. The energy is not enough to ionise the atom but is sufficient to raise the atom to a higher energy level. Here the photon is about to interact with the electron in *Figure 19*.

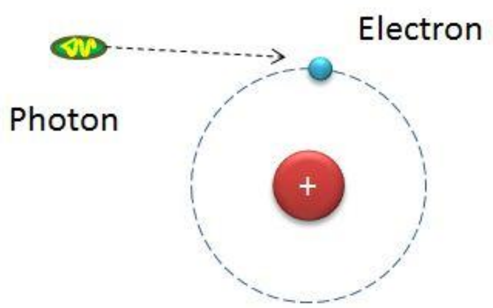


Figure 19 Photon about to interact with an electron.

Remember that a photon is pure energy. It has to be exactly the right energy. All the energy is passed to the electron. It rises to a higher energy level (*Figure 20*).

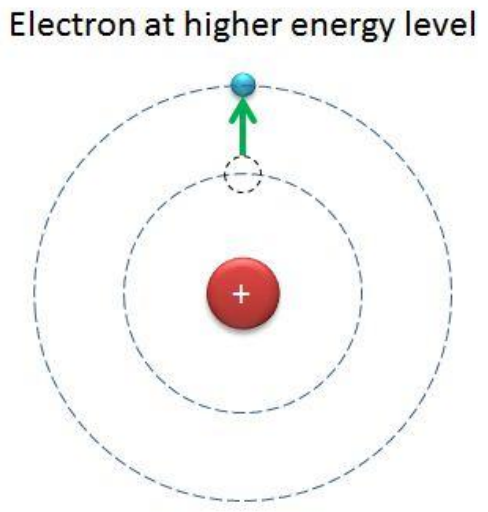


Figure 20 An electron being raised to a higher energy level.

Almost immediately, the electron falls back to its original level which is called the **ground state**. The energy is emitted as a **photon**. The photon travels off in **any** direction, not necessarily the direction it came from. The photon travels in a **straight line** after emission (*Figure 21*).

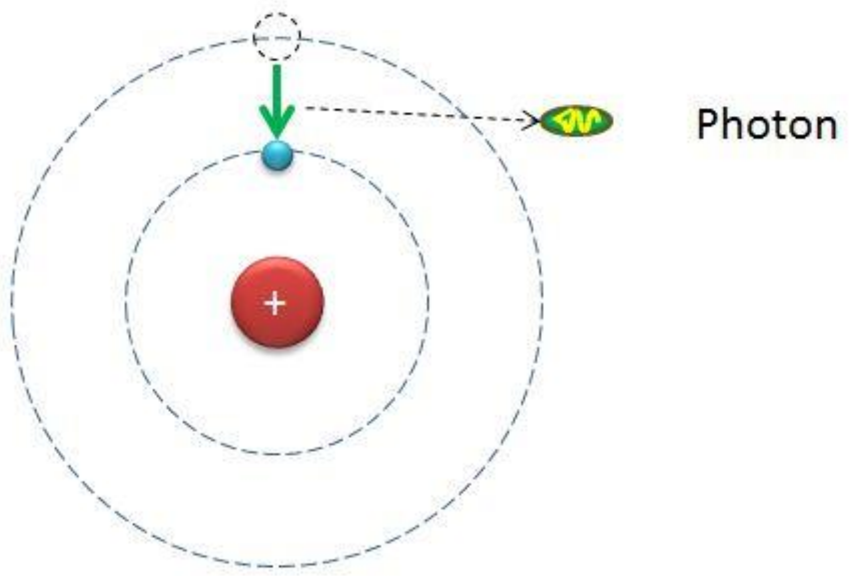


Figure 21Photon emission as electron falls back to a lower energy state.

We have seen that:

- The electron does a job of work in releasing a photon. It **loses potential e**nergy.
- The highest energy level is where **ionisation** occurs. The lowest level is the **ground state**.
- Ionised atoms give out **electromagnetic radiation** as the electrons fall back to the ground state. This may be **visible light**.
- Photons of **sufficient energy** can cause ionisation. This is how gamma rays interact with atoms to ionise them.

3.043 Energy Levels in Atoms

Almost immediately the excited electron falls back to the ground level, emitting **photons**. The picture shows two energy levels in an imaginary atom (*Figure 22*).

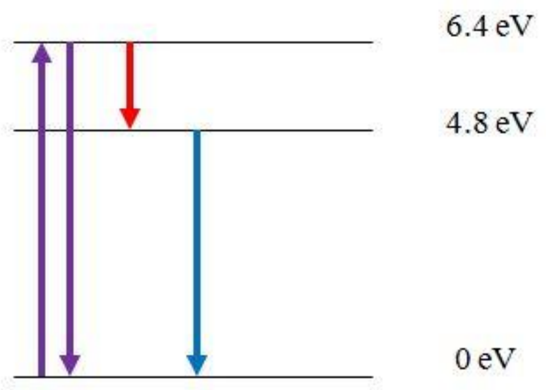


Figure 22 How an electron falls back down from a higher level to the ground state.

Note that the values here are shown as **positive**, the ground state being **zero**. This has been done for simplicity. The ionisation energy of this atom is a lot more than 6.4 eV.

The in-coming photon has to be exactly **6.4 eV**. There are three possible energies for emitted photons:

- 6.4 eV, if the electron falls straight back to the ground state.
- 4.8 eV, if the electron falls from the 4.8 eV level to 0 eV.
- 1.6 eV if the electron falls from the 6.4 eV to the 4.8 eV level.

If the photon is 6.35 eV, it will <u>not</u> be absorbed. It has to be 6.4 eV.

In the example above positive values are given. In most exam questions the following convention is observed:

- The ionisation energy is regarded as 0 eV.
- All other energy levels are negative.
- The most negative energy level is the ground state. In hydrogen, the ground state is -13.6 eV.

Read the question carefully to see if the energy levels are in eV or J. They will show an axis labelled, **Energy / eV** or **Energy / × 10^{-19} J**

Before using any equation, such as $E = hf$, values in **electron volt** (eV) must be changed to **joule** (J)

Electrons can make transitions from any energy level to any other (*Figure 23*).

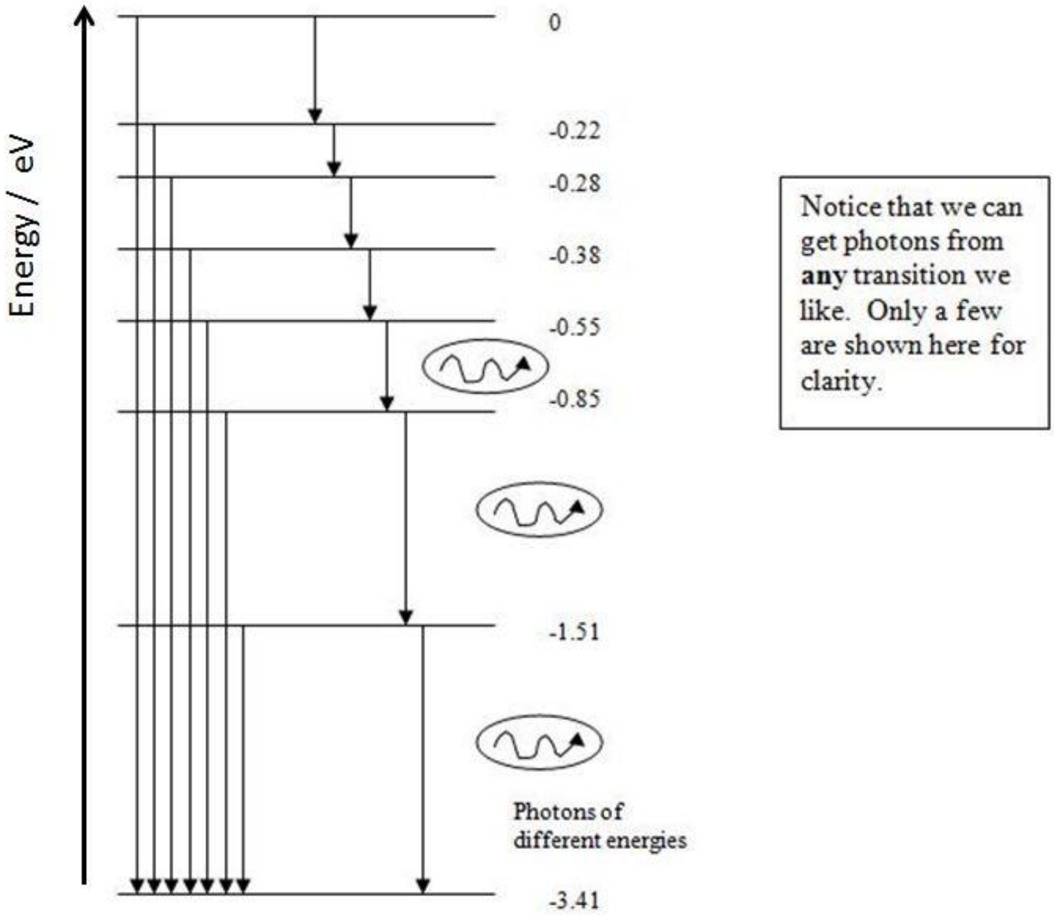


Figure 23 Transitions made by an electron falling back to ground state.

Note that these transitions are those of the simplest atom, the **hydrogen** atom. These transitions give us photons in the **visible spectrum**. In fact, the ground state is at –13.6 eV. So, transitions to the ground state will give photons in the UV region.

The transition from -13.6 eV to 0 eV is the **ionisation energy** of hydrogen, the energy required to strip an electron from the atom (*Figure 24*).

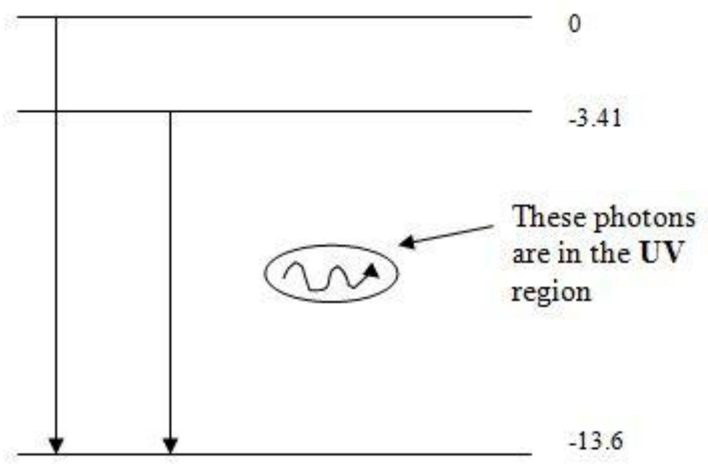


Figure 24 These electron transitions emit photons in the UV region

We need to be aware of the following points:

- The lowest level (-13.6 eV) is the **ground state**. This is the normal configuration of the atom. Energy must be put in to raise the electron to other levels.
- The highest level is the **ionisation** energy.
- Energy levels are not evenly spaced.

We can quantify this in an equation. If an electron is at an excited level (E_1) and makes a transition to a lower level (E_2), then the energy ΔE of the photon given out can be worked out with the equation (*Equation 10*).

$$\Delta E = E_1 - E_2 \quad \text{……. Equation 10}$$

The strange looking symbol Δ is Delta, a Greek capital letter 'D'. It is physics code for 'change in' or 'difference in'.

Since $\Delta E = hf$, we can rewrite *Equation 10* as:

$$hf = E_1 - E_2 \ \ldots\ldots \text{ Equation 11}$$

When photons are absorbed, all their energy is used to raise the electron to the higher energy level. Immediately, the electron falls to the ground state, photons are emitted. The frequency (or wavelength or colour) depend on the transitions. Remember that all transitions will be seen, as there are thousands of millions of atoms. The photons are retransmitted in all directions.

Ionisation of gases and energy levels in atoms have **NOTHING whatever** to do with the photo-electric effect.

3.044 What is the difference between ionisation and excitation?

Ionisation	Excitation
In ionisation, the electron is removed from the atom.	In excitation the electron is not removed, but is raised to a **higher** energy level
As long as the colliding electron has more energy than the ionisation energy the electron will be removed.	The photon or electron causing the excitation has to have exactly the right amount of energy, else no effect is observed.

Tutorial 3.04 Questions

3.04.1

(a) An excited atom loses its energy quickly. How does it do this?

(b) What is the frequency of a photon given out by a transition from -0.85 eV to -1.51 eV? Give your answer an appropriate number of significant figures.

3.04.2

Hydrogen has an ionisation energy of 13.6 eV. Explain what would happen if a hydrogen atom interacted with:

(a) An electron of energy 22.1 eV.

(b) A photon of energy 13.6 eV.

(c) A photon of energy 6.1 eV.

3.04.3

Show that a photon emitted in the transition from -3.41 eV to the ground state in hydrogen is in the UV region.

Tutorial 3.05 Fluorescence	
All Syllabi	
Contents	

3.051 Fluorescence

If photons strike materials, and they have **exactly the right energy**, electrons in the atoms will be **excited**, and be raised to higher energy levels. The photon has to have exactly the right energy for this to work. If it doesn't, the photon will not be absorbed.

Note that atoms can be **ionised** by photons that have energies greater than the ionisation energy. The energy value does not have to be exact.

We have seen how the electron goes back to its **ground state** after being excited. It emits a photon according to the difference in energy levels. It's a bit like falling down the stairs (do not try this at home):

- You can fall down the whole flight of stairs.
- You could bounce from stair to stair.
- Or any combination...
- The bigger the fall, the more it hurts...

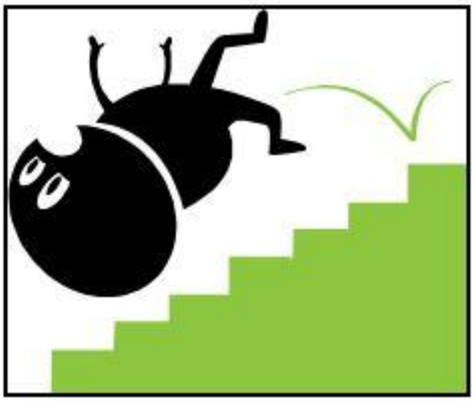


Figure 25 The bigger the fall, the more it hurts.

There are huge numbers of electrons being excited and falling back to their ground state, so all possible transitions are being made at the same time.

The bigger the **transition**, the **more** energy is involved, so the **shorter** the wavelength.

If some materials are exposed to ultra violet light, they absorb the UV radiation and will reradiate it. Some electrons will fall straight back to their ground state, giving off UV light, but others will go through several lower energy transitions, giving off visible light. They appear to glow under UV light, a phenomenon called **fluorescence**. There are a number of materials that can be made to fluoresce.

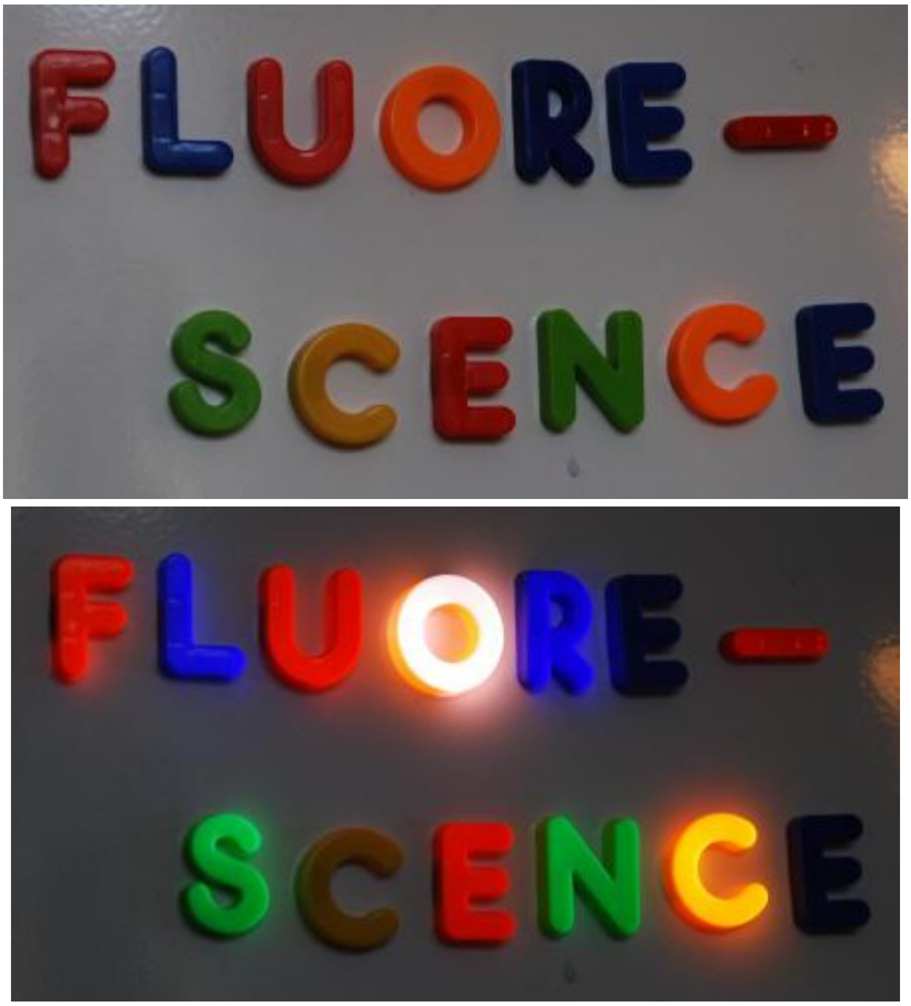


Figure 26 Fluorescence. Both pictures by Pieter Kuiper (Wikimedia Commons)

Fluorescence is the correct spelling, not flourescence. Yes, I have made that mistake plenty of times! Don't write flowerescence either. Yes I have seen it!

3.052 Fluorescent Tubes

The **fluorescent** tube (found in all offices) uses this effect. It is full of **mercury vapour**. It is set up like this (*Figure 27*).

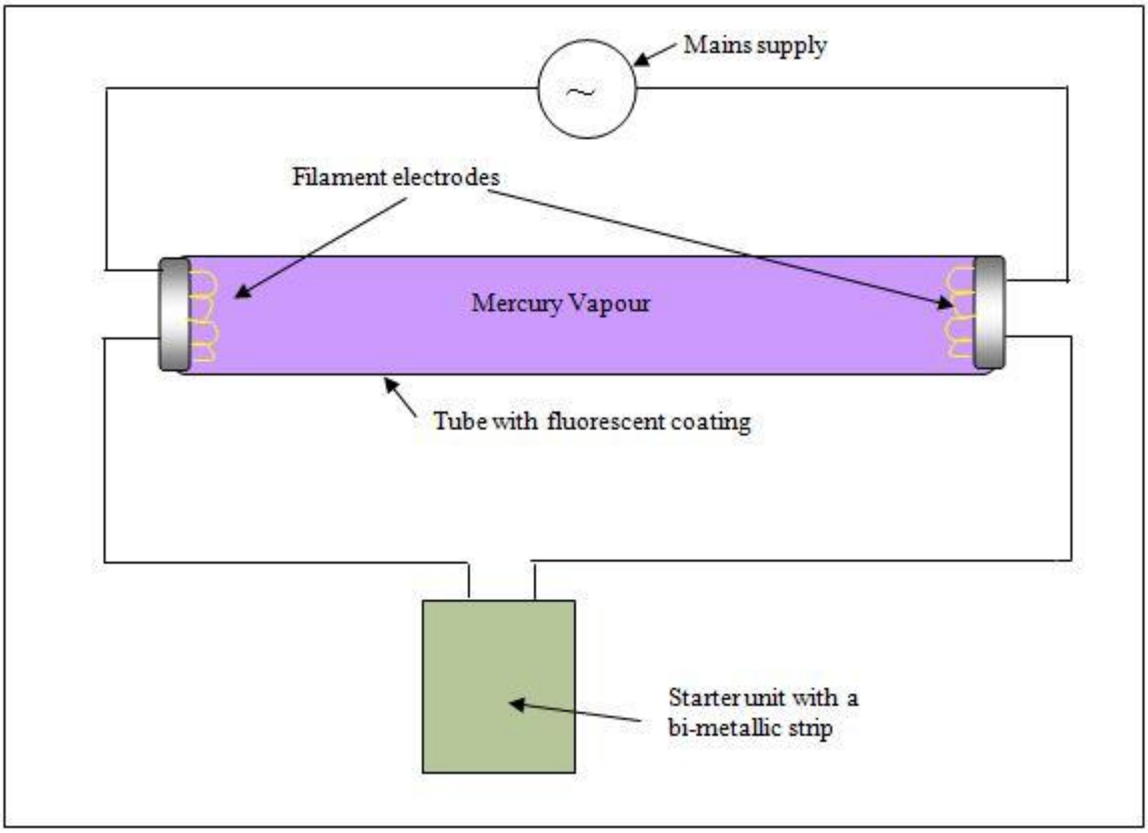


Figure 27 Simplified schematic for a fluorescent tube

With a **fluorescent coating**, they are very useful (even if rather unpleasant).

- **Ionisation** of mercury atoms occurs because electrons collide with the atoms and knock electrons off.
- Electrons then go back to the mercury atoms and return to the **ground state**. The emit **photons** as they fall down the energy ladder.
- Some photons are in the visible range, but most are in the **UV range**.
- A **fluorescent coating** absorbs the UV light and electrons in the coating material are excited. They are raised to a higher energy level.
- Then they fall back to their ground state. They emit photons of **visible light**.

The way the fluorescent tube works is shown in the picture (*Figure 28*)

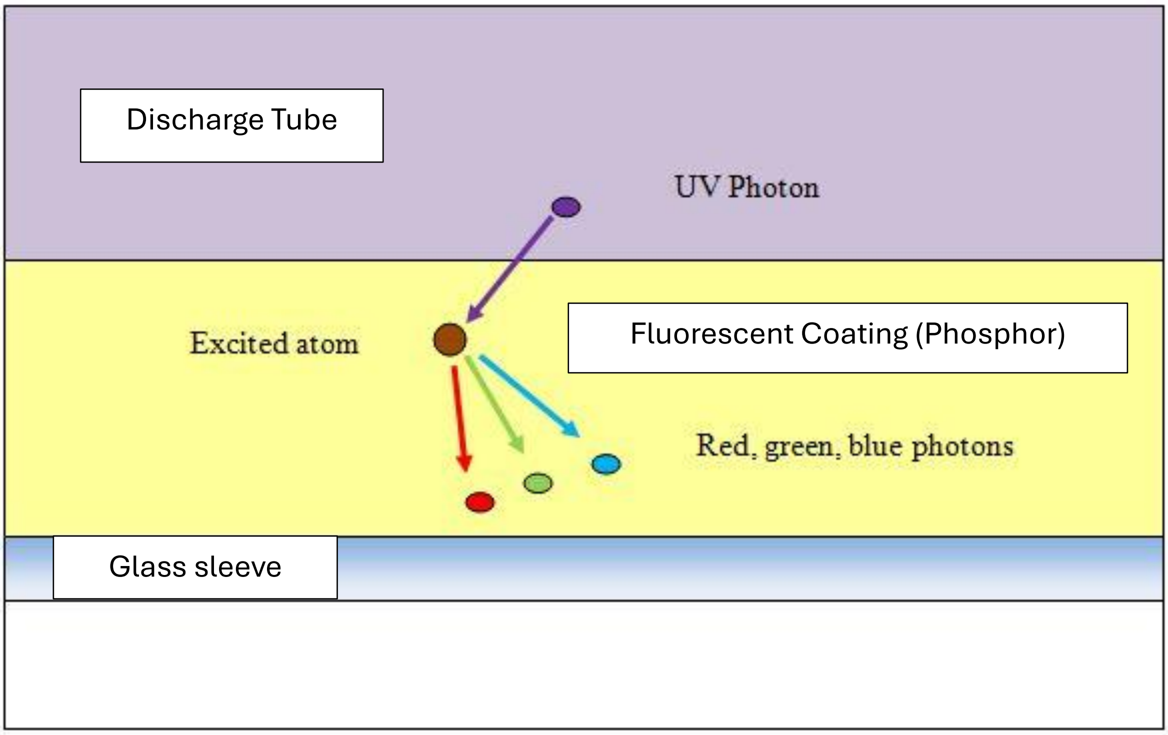


Figure 28 Explaining how a fluorescent tube work

The white light is made from a **mixture** of red, green, and blue photons. These arise from different transitions of the electron as it falls through different energy levels, as shown on this simplified representation (*Figure 29*).

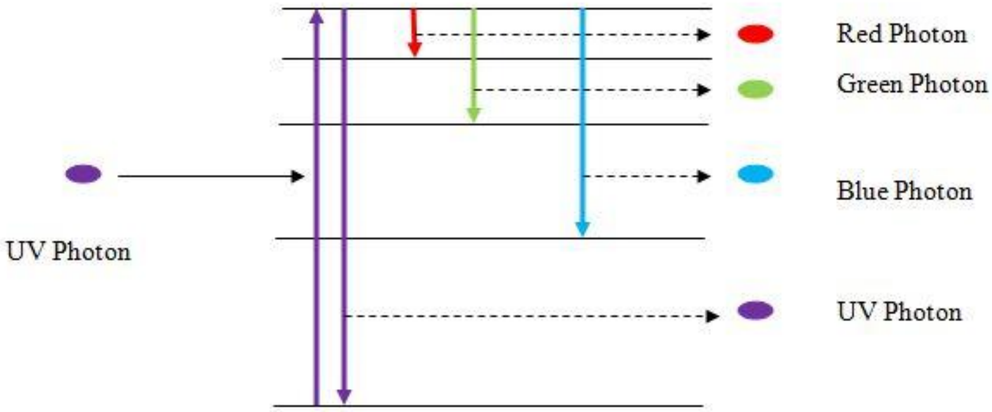


Figure 29 Showing the transitions that give rise to photons of different colours

The UV **photons** excite atoms in the **fluorescent coating** on the inside of the discharge tube. The coating is often called the **phosphor**. The excited phosphor emits a mixture of **red**, **green** and **blue** photons. These mix to give **white** light. Fluorescent tubes give a slightly green **colour cast** on photographic film that is designed for daylight. This indicates the presence of more photons in the green region (Figure 30).

2.043 Advantages and disadvantages

You could well be asked a question about the advantages and disadvantages of fluorescent lighting.

Figure 30 Fluorescent tubes give a slight green cast.

Advantages:

- They use a lot less electricity than an ordinary filament lamp (**incandescent** lamp). An 11-watt fluorescent lamp gives out as much light as a 60-watt incandescent lamp. Therefore, it makes sense to use fluorescent bulbs as less energy is wasted as **heat**.
- Also, the bulbs last a lot longer than the incandescent lamps.
- Incandescent (tungsten filament) lamps are no longer widely available.

Disadvantages

- Fluorescent lamps are NOT environment friendly. They have mercury in them, although it is in small amounts. Mercury is a highly toxic heavy metal, and breathing in mercury vapour is dangerous. If a fluorescent lamp is broken, then there are risks to people in the room.

- **Disposal** has to be carried out with care, as mercury could get into ground water.
- They are expensive to buy.
- They may last longer, but they do not last for ever. A flickering tube is unpleasant and distracting.
- A normal fluorescent tube flickers at 50 Hz. Stroboscopic effects can be seen. Nowadays there are **high frequency fluorescent lamps** that avoid this but are a lot more expensive. If they fail, the whole fitting has to be replaced.
- While it is easy to replace an incandescent bulb with a brighter one, the same is not true for fluorescent lamps. New fittings have to be bought.
- Although a lot of effort has been put in to make the designs more homely, they still look **unpleasant**.
- The light is **harsh** and can make people feel unwell.
- They cannot be dimmed easily.

Photographs taken with daylight film would show that the fluorescent lamps would give a slightly green tinge to the pictures. A filament lamp gives an orange tinge. The effect is less marked with digital cameras, as most cameras will compensate for any colour cast, but you can still see the orange tinge to the lamp behind the door (*Figure 31*).

Figure 31 Incandescent lamps gave an orange cast.

Many people still preferred the warmth of a filament lamp and continued to buy them in preference to the fluorescent fittings. Attempts were made to make fluorescent units more attractive, so that they would fit home décor. They were not that attractive, though.

In the exam, fluorescence is quite a likely subject for an essay question (worth 6 marks in the AQA papers). To do well in these questions, you must not only get all the points but also present them in good English. You will be expected to write about three quarters of a side of A4, about the upper limit for many physics students doing the AQA syllabus.

The question below gets you to consider the points you would raise when attempting one of these questions. The key thing is to keep your answer short and to the point. Do not be tempted to add unconsidered supplementary material (**waffle**) as it not only will not give you any extra marks, but also you could lose marks due to contradictions. Use **good English** and well-constructed sentences. Keep the sentence structure simple. Avoid figures of speech like metaphors; you are not writing a great literary masterpiece.

The most modern form of lighting is based on **light emitting diodes** (LEDs). Their light is much more pleasant than fluorescent lamps. They use less electricity. This one (Figure 32) takes 3 watt (compared to 33 W for the filament equivalent). They are much more expensive, though.

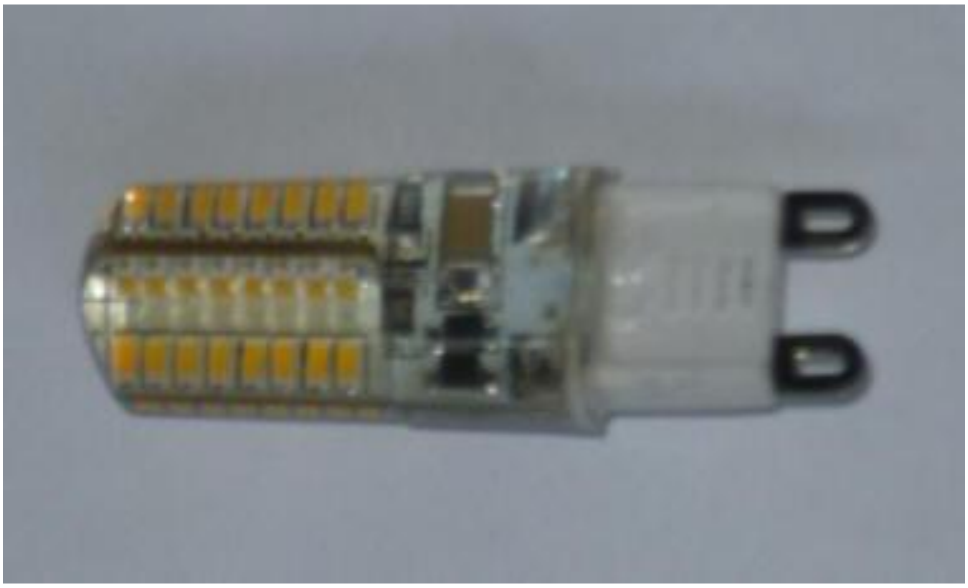


Figure 32 An LED lighting unit.

They are meant to last for tens of thousands of hours. Except they don't (*Figure 33*).

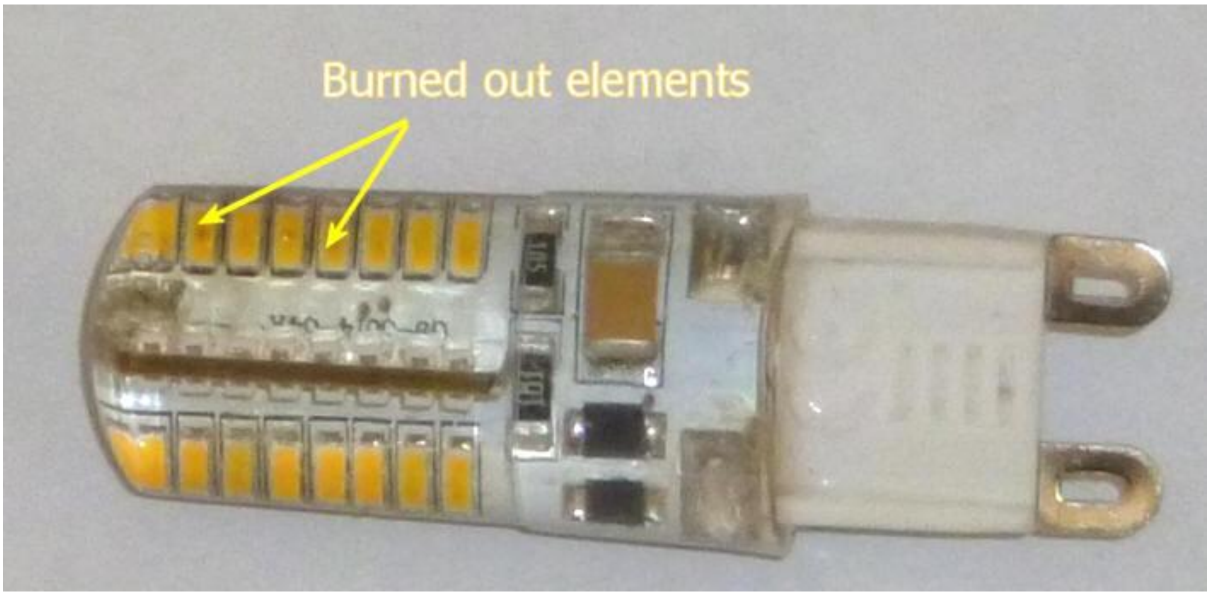


Figure 33 A failed LED lighting unit

Nowadays, LED bulbs are widely used in preference to incandescent lamps. Mostly LED units are shaped like traditional bulbs (*Figure 34*). It is possible still to get Halogen incandescent lamps, as shown in *Figure 34*.

Figure 34 Different kinds of bulbs

LED lamps can have their LED arrays arranged as a “filament” that glows in a visually very pleasing manner.

Tutorial 3.05 Questions

3.05.1

Explain in as much detail as you can how the electrical energy that is put into a fluorescent tube in a classroom (or office) is converted into light energy that is useful in lighting a room.

Tutorial 3.06 Wave-Particle Duality	
All Syllabi	
Contents	
3.061 de Broglie Relationship	3.062 Electron Diffraction

3.061 De Broglie's Relationship

The French physicist and aristocrat, **Louis de Broglie** (1892 – 1987) [pronounced '*de Broy'*], reasoned that if *waves* have particle properties, it was reasonable to suppose that *particles* had wave properties. He devised the relationship that states that particles have wave properties. These are often called **matter waves**.

Figure 35 Louis de Broglie (1892 - 1987)

He combined the following equations:

- Energy of photons:

$$E = hf \quad \text{……. Equation 12}$$

- Einstein's mass equivalence:

$$E = mc^2 \quad \text{……. Equation 13}$$

Therefore, combining *Equations 12* and *13*, we can write:

$$hf = mc^2 \text{ ……. } \textit{Equation 14}$$

Now

$$f = c/\lambda \text{ ……. } \textit{Equation 15}$$

So, we can combine Equations 14 and 15 to give:

$$mc = \frac{h}{\lambda} \text{ …….. } \textit{Equation 16}$$

The term mc is mass × speed, which gives us the value of **momentum**. We give momentum the code p.

We can rewrite the equation as

$$\lambda = \frac{h}{p} \text{------------- } \textit{Equation 17}$$

or

$$\lambda = \frac{h}{mv} \text{........ } \textit{Equation 18}$$

Therefore, every particle with a momentum has an associated de Broglie wavelength, even something as absurd as a car travelling at 20 m s^{-1}.

3.062 Electron Diffraction

Electrons can be shown to have wave properties by the simple use of an **electron diffraction tube**. A slice of carbon is placed in a beam of electrons so that the electrons **diffract**, just like waves (*Figure 36*).

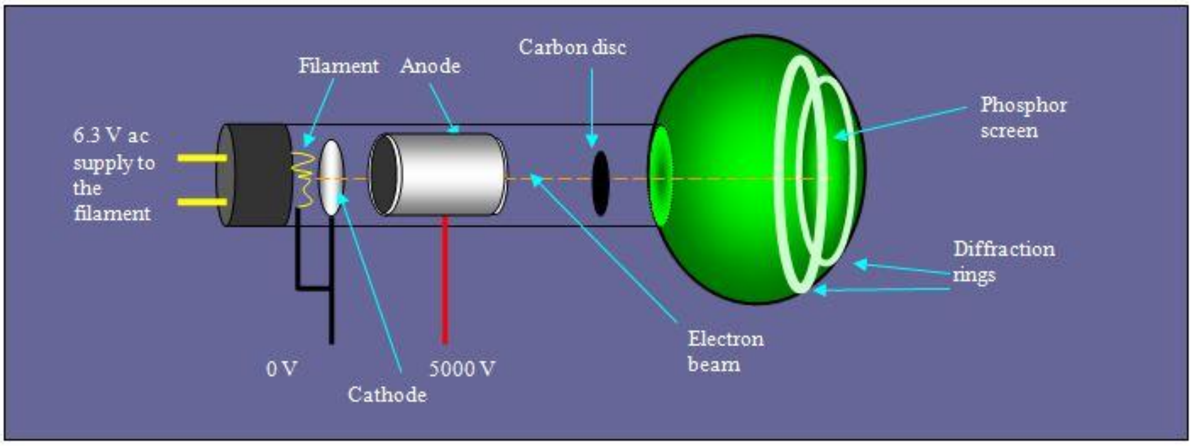


Figure 36 Showing electron diffraction

We need to note a couple of points:

- λ is the **de Broglie wavelength**.
- Strictly speaking we should count the mass and speed as **relativistic**. As the speed of particles approaches the speed of light, the mass increases as kinetic energy is turned into mass. We will not worry about this at this stage.

Diffraction is a wave property. Interference patterns from electrons also can be observed.

An **interference** pattern of water waves looks like this (*Figure 37*)

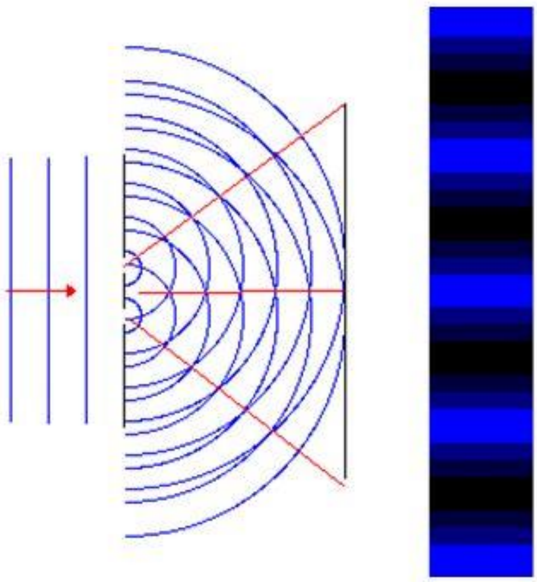


Figure 37 A diffraction pattern as seen in water waves

A similar pattern can be observed using electrons. Images from light waves are very complicated interference patterns. Images can be made from very complicated interference patterns using an electron beam in an electron microscope.

The wave properties of electrons have led to the development of the **electron microscope**, which allows magnifications much bigger than was ever possible with the light microscope. A good light microscope can magnify up to 1000 times. The electron microscope can magnify up to about 1 million times and can reveal the existence of individual atoms. The electron beams are focused by magnets just like the lenses on a microscope.

Do not confuse the de Broglie equation with the photon energy equation. They look superficially similar, but they are not relevant to each other.

<u>Conclusion</u>

- Electrons, which are definitely **particles**, have **wave-like properties**.
- The **wave behaviour of electrons** explains how the electron microscope works.

The wave properties of particles are called **matter waves**.

Tutorial 3.06 Questions

3.06.1

What was de Broglie's hypothesis?

3.06.2

Diffraction is associated with waves. Give two examples of diffraction with waves.

3.06 3

What is the evidence that electrons behave like waves?

3.06.4

What is the de Broglie wavelength of an electron travelling at 2.0×10^{6} m s^{-1}? Give your answer to an appropriate number of significant figures.

Tutorial 3.07 Radiation Pressure (Extension only)	
Welsh Board	
Contents	
3.071 Radiation Force	3.072 Radiation Pressure

Note that this topic will require previous study. Do not attempt this until you are confident you have the background to this.

We know that **pressure** is defined as **force per unit area**:

$$p = \frac{F}{A}$$ .... *Equation 19*

It may be a surprise, but there is a **pressure** from the photons arriving from the Sun. This is called **radiation** pressure. Like any other pressure, its units are Pa.

It has a value of about 10 × 10^{-6} Pa, which is not exactly going to crush you. Atmospheric pressure, for comparison, is about 1 × 10^{5} N m^{-2}.

All electromagnetic radiation results in radiation pressure.

3.071 Radiation Force

When radiation strikes a surface, momentum from the particles is transferred to the surface. The change in momentum leads to a **force**.

You might (correctly) think that photons have no mass (hence zero momentum), but **relativity** allows them to have momentum by this general equation (Equation 20).

$$E^2 = m^2c^4 + p^2c^2$$ ……… *Equation 20*

This is consistent with mass and energy being equivalent.

When mass is zero, we get the following result:

$$E = pc$$ .... *Equation 21*

And by rearranging *Equation 21*:

$$p = \frac{E}{c}$$ .... *Equation 22*

Where:

- p = momentum (N s).
- E = photon energy (J).
- c = speed of light (m s^{-1}).

We also know that **force** is defined as **rate of change of momentum** (Newton II):

$$F = \frac{\Delta p}{\Delta t}$$ .... *Equation 23*

Rearranging:

$$\Delta p = F\Delta t$$ .... *Equation 24*

We can combine the *Equations 23* and *24* above by writing:

$$F\Delta t = \frac{E}{c}$$ .... *Equation 25*

And then we write an expression for F (*Equation 26*).

$$F = \frac{E}{c\Delta t}$$ .... *Equation 26*

We can see that there is an ***energy ÷ time*** component. This is **power**, so we can write:

$$F = \frac{P}{c}$$

.... *Equation 27*

P is the power.

<u>*Worked Example*</u>

A red laser pointer has a power of 1.0 mW. The wavelength of the laser light is 650 nm.

(a) Work out the energy of each photon.
(b) Work out the momentum of each photon.

Planck's Constant = 6.63×10^{-34} Js
Electronic charge = 1.60×10^{-19} C

<u>*Answer*</u>

(a) Use $E = \frac{hc}{\lambda}$ to give the photon energy.

$$E = \frac{6.63 \times 10^{-34}\text{Js} \times 3.0 \times 10^{8}\ \text{ms}^{-1}}{650 \times 10^{-9}\ \text{ms}^{-1}}$$

= 3.06×10^{-19} J

(b) Use $p = \frac{E}{c} = \frac{3.06 \times 10^{-19}\ \text{J}}{3 \times 10^{8}\ \text{ms}^{-1}} = \mathbf{1.02 \times 10^{-27}\ Ns}$

Note the unit for momentum as Ns, rather than kg ms^{-1} since a photon has zero mass.

3.072 Radiation Pressure

We know that:

$$p = \frac{F}{A}$$

.... *Equation 28*

Where p is the pressure.

We also know that

$$F = \frac{P}{c}$$

.... *Equation 29*

So, we can divide the equation above by the area:

$$\frac{F}{A} = \frac{P}{Ac}$$

.... *Equation 30*

Power divided by area gives **intensity**, so we can write:

$$p = \frac{I}{c}$$

.... *Equation 31*

where I is the intensity (W m^{-2}).

The wavelength does not matter, because the lower the photon energy, the more photons are needed for a given power.

Note that both pressure and momentum have the same code, p.

Make sure you know in which context you are using p.

Radiation pressure can be used for **optical refrigeration** which the vibration of atoms can be reduced as they interact with incoming photons from a laser.

Worked Example
A red laser pointer has a power of 1.00 mW. The wavelength of the laser light is 650 nm. (a) The photon energy is 1.91 eV. Calculate the number of photons emitted from the laser every second. (b) Work out the force exerted every second, assuming that the laser light photons travel in one direction only. (c) The aperture of the laser is 0.5 mm in diameter. What is the radiation pressure?

Answer

(a) Convert eV to joules by multiplying by 1.60×10^{-19} C

$$1.91 \text{ eV} \times 1.60 \times 10^{19} \text{ C} = \mathbf{3.06 \times 10^{-19}\ J}$$

Now we can work out the number of photons, n, per second.

$$n = \frac{P}{E} = 1.00 \times 10^{-3} \text{ Js}^{-1} \div 3.06 \times 10^{-19} \text{ J}$$

$$\boldsymbol{n = 3.27 \times 10^{15}\ \mathrm{s^{-1}}}$$

(b) Use:

$$F = \frac{P}{c}$$

$$F = 1.00 \times 10^{-3} \text{ W} \div 3.00 \times 10^{8} \text{ ms}^{-1} = \mathbf{3.33 \times 10^{-12}\ N}$$

(c) Work out the area of the aperture:

$$A = \pi r^2 = \pi \times (0.25 \times 10^{-3} \text{ m})^2 = 1.96 \times 10^{-7} \text{ m}^2$$

Now we can work out the radiation pressure.

$$p = \frac{F}{A} = \frac{3.33 \times 10^{-12} \text{ N}}{1.96 \times 10^{-7} \text{ m}^2}$$

$$p = \mathbf{1.70 \times 10^{-5}\ N\ m^{-2}}$$

Tutorial 3.07 Questions

3.07.1

How much greater is the atmospheric pressure than the radiation pressure?

3.07.2

A light source has a power of 6.0 W. What is the force from its photons?

3.07.3

The intensity of light striking the Earth's surface at a certain spot is 550 W m^{-2}. What is the radiation pressure?

3.07.4

Explain how a photon of zero mass can have momentum.

3.07.5

Show that the radiation force is given by the simple equation:

$$F = \frac{P}{c}$$

Where F is the force, P is the power of the source, and c is the speed of light.

3.07.6

It is proposed that a spacecraft is to be propelled by four 10 kW lasers each emitting photons of wavelength 122 nm.

(a) Calculate how many photons will be emitted per second with all four motors running.

(b) Calculate the force from these photons.

(c) The spacecraft has a mass of 1500 kg. Calculate its acceleration, assuming that the spacecraft is in deep space. Comment on the viability of such a propulsion system.

Tutorial 3.08 How the LASER works (Extension only)	
Welsh Board and CEA Board	
Contents	

For students studying the Welsh Board and CEA syllabus

LASER is an acronym for ***L**ight **A**mplification by **S**timulated **E**mission of **R**adiation*. Trips off the tongue, doesn't it? But good for a pub quiz.

The invention of LASER is credited to Theodore Maiman (1927 - 2007) or to Gordon Gould (1920 - 2005). (There was a lot of legal action as a result.) Both were American Physicists who developed the work of two American theoretical physicists, Charles Townes (1915 - 2015) and Arthur Schawlow (1921 - 1999).

The properties of LASER light are that:

- It's **coherent** and **monochromatic**.
- The ray is **parallel** with very little divergence.
- The light can be emitted **continuously**, or in **very short pulses,** down to femtoseconds (fs - 1×10^{-15} s).

These make the LASER particularly useful for optics experiments in school and college labs. There are many other uses, which we will look at later.

3.081 Optical Pumping

The LASER itself is quite simple, with no moving parts. Here is a diagram (*Figure 38*).

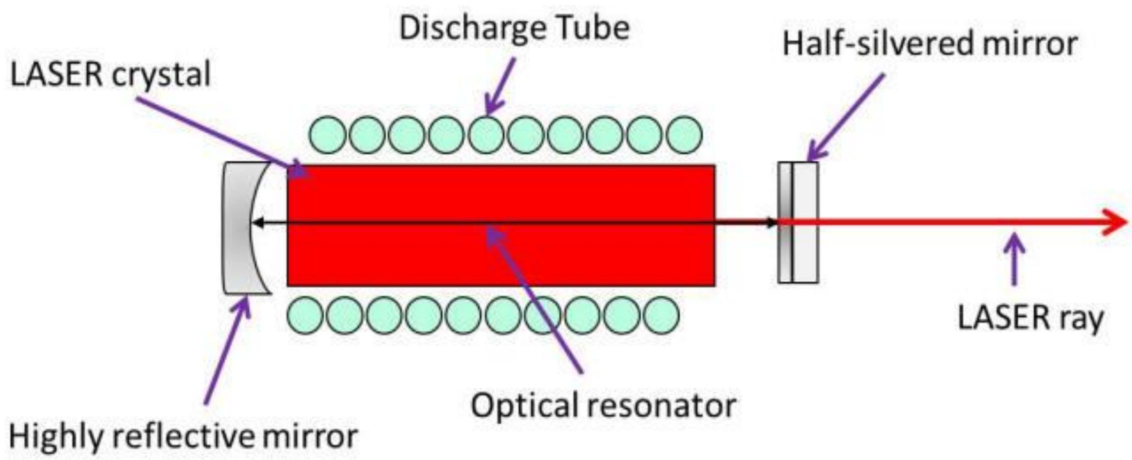


Figure 38 General layout of a LASER

The optical resonator consists of a crystal of material such as sapphire (Al_2O_3) which is doped with ions of rare earth metals. The crystal is called the host crystal, and the ions are of transition elements like titanium, ytterbium, and chromium.

The discharge tube is a larger version of a photographic flash bulb, which gives off an intense white light. The intense light passes into the space between the two mirrors, which is referred to as the optical resonance cavity, or laser cavity. The resonating light between the two mirrors becomes weaker as some of the energy is lost on reflection. The lost energy is supplemented by the photon emission from the LASER crystal.

This extra energy is referred to as **optical pumping**.

The crystal emits LASER light when it is exposed to the intense light, by **stimulated emission**, i.e. photons being emitted by interaction of atoms with other photons.

3.082 Stimulated Emission

There needs to be sufficient energy for stimulated emission to occur. If not, the crystal will not produce LASER light. The optical pumping power needs to be above the **LASER threshold**. Then the stimulated emission rapidly rises until the crystal is **saturated**. Let's look at the mechanism.

Incident photons of exactly the right energy excite the atom so that an electron is raised to a higher energy level. In normal (**spontaneous**) electron excitation, the photon is absorbed. The electron is raised to the high energy level. Then as the electron falls back to the ground state, it emits a photon of the same energy. However, in this case, the phase and direction are random. Light will be given off, but this will not result in stimulated emission.

In LASER light, it's a rather different. The electron is excited by external photon at exactly the right frequency (hence energy). As the electron makes its transition between the ground and excited states (neither of which have any magnetic properties), it gains a **magnetic dipole** that makes it act like a tiny magnet. This **oscillates** at the photon frequency and makes it more likely that the electron will achieve the excited state. Therefore, more electrons are raised to the excited state than would happen in spontaneous excitation. The oscillations of the dipole are responsible for the **optical resonance**. Almost immediately the electron falls back to the ground state, emitting another photon. This is shown below in *Figure 39*.

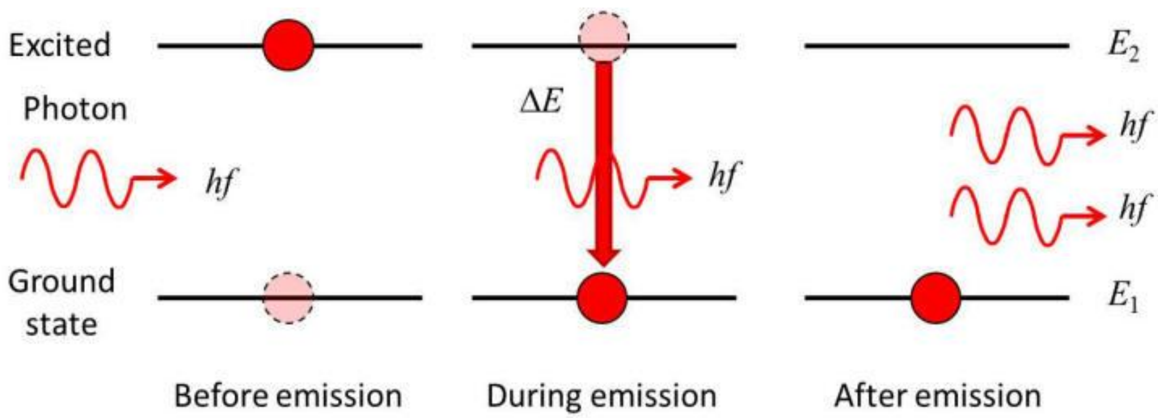


Figure 39 Stimulated photon emission

Rather than just one emitted photon, we get a second emitted photon by **stimulated emission** (*Figure 39*). This has the same phase relationship with the first photon. Here we see it as being in phase. We can calculate the photon energy using this equation:

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

.... Equation 32

After emission, we have two photons that are **in phase**. Stimulated emission of itself will not cause LASER action. We need another step, **population inversion**.

3.083 Population Inversion

In spontaneous excitation of atoms, the vast majority of the atoms are in the ground state, with just a small proportion of the atoms excited.

This is the case when the process of light amplification is started by the process of **optical pumping**. The photons are moving in random directions with no constant phase relationship. So, the light given off is not coherent. However, many of these photons are trapped in the optical resonator, the space between the highly reflective mirror and the half-silvered mirror. Some are lost to the process by absorption to release a single photon in a spontaneous event. Others, however, cause stimulated emission in excited atoms, releasing a second photon that goes off in the same direction and has the same phase relationship. So, we start to get **optical amplification**, resulting in coherence.

The number of coherent photons produced by stimulated emission increases. The optical amplification has a factor that is greater than 1.

At a certain point, we find that more atoms are in the excited state than in the ground state. We have achieved the **LASER threshold**. Suppose we have N_1 atoms in the ground energy state E_1, and N_2 atoms in the excited energy state E_2, the photon absorption is the main process and the light level falls.

If $N_1 = N_2$, the absorption balances the emission. The material is said to be **optically transparent**.

If $N_2 > N_1$, then the LASER threshold is passed. We say that there is **population inversion**, meaning that the number of excited atoms is greater than the number of atoms at the ground state.

As the process continues, the more atoms are excited, until eventually all atoms are excited. We say that the crystal is **saturated**. The LASER is in **steady state**.

Half the light is reflected at the half-silvered mirror called the **output coupler**, while half the photons pass through the output coupler.

3.084 The Need for More than Two Levels

In the discussion above, we modelled a LASER system that was based on two energy levels, the excited level, and the ground level. However, this does not work in practice. If the energy from the pump is the same as the difference between the ground and the excited state, we would get a combination of:

- Stimulated emission.
- Spontaneous emission.
- Excited atoms being knocked back to the ground state.

Surprisingly, it is possible for an atom to be **de-excited** by interaction with a photon.

With a two-level system, the highest proportion of atoms excited by stimulated emission can only be 50 %, with the rest being at the ground state or undergoing spontaneous emission of photons. Therefore, at best, we would get optical transparency. We do NOT get stimulated emission. We need to have three or even four levels. The atoms need to be pumped up to a third (or even fourth) level to maintain the population inversion. We will look at just three levels (*Figure 40*).

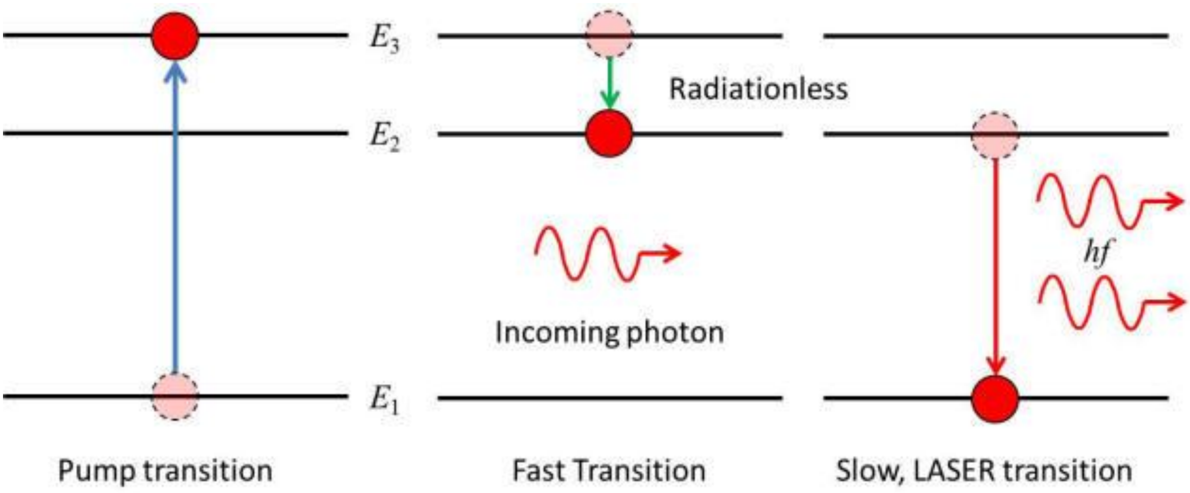


Figure 40 Transitions between three levels

The pumping occurs at a photon energy of $E_3 - E_1$, to excite the atom to energy level E_3. Level E_3 is sometimes called the **pump band**.

Then the electron drops from E_3 to E_2. It could be a spontaneous emission, but more often it's a rapid drop **without giving off a photon**. The energy is simply transferred as vibrational kinetic energy to heat up the surrounding material. The lifetime of this transition is **short**.

When the electron falls from E_2 to the ground state, the lifetime is very much longer than the transition lifetime from E_3 to E_2. Since the population at E_3 is much lower than that at E_2, we can say that most of the atoms are in the E_2 state. There are many more atoms at E_2 than are at E_1, so a population inversion occurs, leading to stimulated emission.

The pumping of the electrons has to be done strongly to get over half the atoms to level 3 and thence to level 2. This makes the laser rather inefficient. So, a more efficient laser can be achieved with a **four-level system**. The idea is shown in the diagram (*Figure 41*).

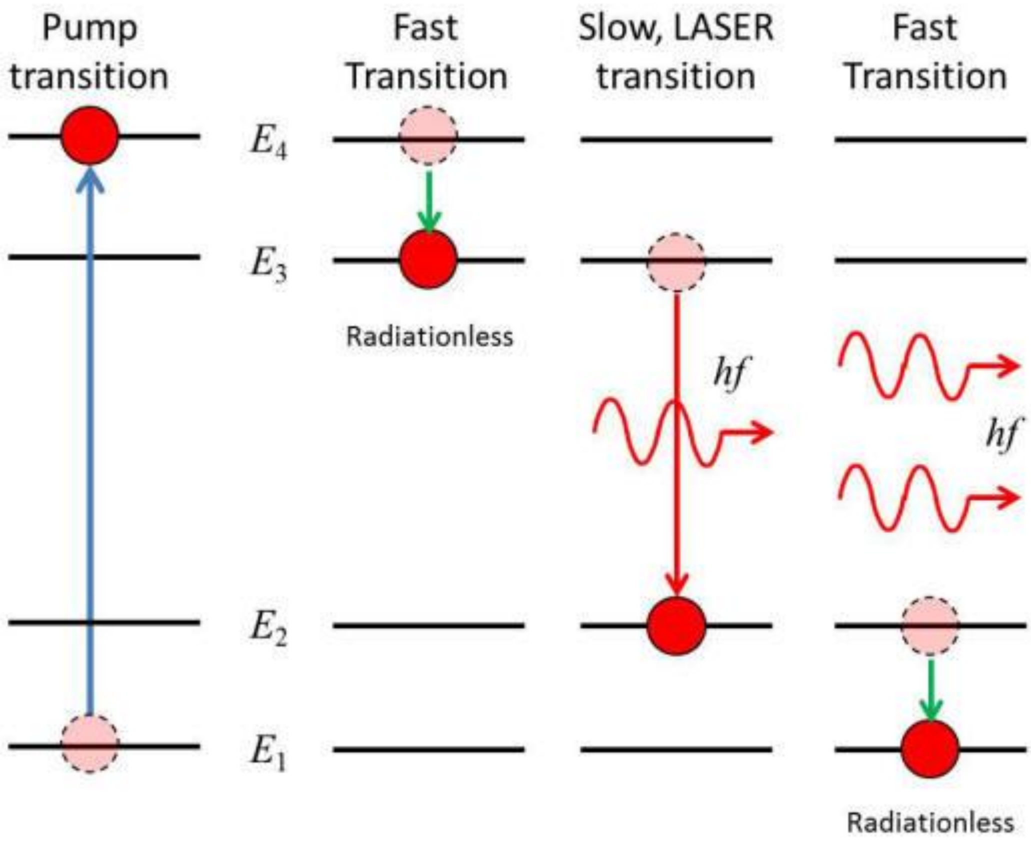


Figure 41 Electron transitions between four energy levels to produce photons

The transition that gives the stimulated emission is E_3 to E_2. Because the transition is very rapid from E_4 to E_3, the number of electrons at E_4 is very low. The number at E_3 is high. At E_2, the number of electrons is very low, since they have fallen rapidly to the ground state. Therefore, the population inversion is more easily achieved. Most LASER sources are of this type.

3.085 Different Types of LASER

We have looked at the crystal LASER to explain how lasing works. They are often called **solid state** LASER. They can give a range of wavelengths. We tend to associate them with red light, as the **red-light** LASER is most often used in schools and colleges. The wavelength, which gives rise to the colour, is determined by the material in the LASER crystal.

There are other types:

- **Gas** LASER - use helium or helium-neon to give red light. Carbon dioxide emits in the far infra-red and is used for cutting materials.
- **Eximer** LASER (eximer comes from *excited dimer*) - use reactive elements like fluorine, mixed with inert gases like argon. They emit UV laser light.
- **Dye** LASER - uses organic dyes as lasing media. They can emit a range of wavelengths.
- **Semiconductor** LASER - they are not the same as the solid-state LASER, as the pumping is done electronically. They may be referred to as the diode LASER. They are very small and cheap. They can give visible light but are more commonly used in the infra-red range.
- **X-ray** LASER - are huge machines that are expensive to run, requiring the collaboration of several countries. They are used for high energy physics experiments.

3.086 Uses of the LASER

There are many uses of the LASER, other than teaching in school and college optics. Other uses include:

- Cutting objects.
- Medical uses, including cauterising (sealing) cut blood vessels and cutting out cancerous tissue.
- Bar-code readers in shops.
- Reading heads in CD players.
- Laser levels using the idea that LASER light travels in a straight and parallel beam.
- Many uses by the military.
- Infra-red diode lasers are used to transmit data along optical fibres.
- LASER pens used by lecturers.
- LASER light shows.

3.087 Safety

The concentrated nature of LASER light makes it potentially **very dangerous**. You must *never* stare into a LASER beam, even a very low-powered one. **It will blind you.** The intensity will burn the retina, and scar tissue will replace the cones. When working with a LASER, you must work under the supervision of your tutor, and wear goggles that will protect you against LASER light.

LASER pens are available at very low prices. They are NOT toys. Some moronic people think that shining LASER pointers at the pilots of aeroplanes coming in to land is some kind of joke. The consequences of such behaviour need no explanation, and the punishments meted out to offenders are severe.

Tutorial 3.08 Questions

3.08.1

What is meant by the terms **monochromatic** and **coherent**?

3.08.2

A LASER emits light of wavelength 620 nm.

(a) Calculate the energy difference that gives rise to photons of this wavelength. Give your answer in joules and electron-volts.

(b) Work out the energy level E_2 if E_1 is -15.6 eV.

(Planck's Constant = 6.63×10^{-34} J s)

3.08.3

What is meant by population inversion?

3.08.4

Explain why a LASER needs to have at least 3 energy levels. What are the features of the energy levels?

3.08.5

A school LASER has a power of 1.5 mW. The wavelength emitted is 620 nm. The LASER beam passes through a hole that is 2.0 mm in diameter. It is being used in an optics demonstration in the physics lab.

(a) Which data item in the question is irrelevant? Explain your answer.

(b) Calculate the intensity.

(c) Hence calculate the radiation pressure exerted on the screen at the front of the physics lab.

Answers to Questions

Tutorial 3.00

3.00.1

Very bright red light has a very high amplitude.

Therefore, it should be able to remove electrons easily.

These does not happen.

Dim UV light removes electrons,

even through its amplitude is very small.

3.00.2

Use

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

$$E = \frac{6.63 \times 10^{-34}\ \text{J s} \times 3.0 \times 10^{8}\ \text{m s}^{-1}}{350 \times 10^{-9}\ \text{m}} = \mathbf{5.7 \times 10^{-19}\ J}$$

3.00.3

5.68×10^{-19} J ÷ 1.6×10^{-19} J eV^{-1} = 3.55 eV = **3.6 eV** (2 s.f.)

3.00.4

$\lambda = hc/E$ = (6.63×10^{-34} J s × 3.0×10^{8} m s^{-1}) ÷ (10.3 eV × 1.6×10^{-19} J eV^{-1})

= **1.21×10^{-7} m** (= 120 nm)

This is in the UV region

Tutorial 3.02

3.02.1

Electron 1 has the most kinetic energy

This is because it is very close to the surface

so little work is needed to get it out.

3.02.2

Electron 2 has the least kinetic energy.

This is because it was less close to the surface.

So, a lot of work was needed to get it out.

3.02.3

Maximum kinetic energy is represented by 3 eV

E_k = 3 eV × 1.6 × 10^{-19} J eV^{-1} = **4.8 × 10^{-19} J**

3.02.4

Maximum energy = 2.6 eV × 1.6 × 10^{-19} J eV^{-1} = 4.16 × 10^{-19} J

$\phi = E/h$ = 4.16 × 10^{-19} J ÷ 6.63 × 10^{-34} J s = 6.27 × 10^{14} Hz

$\lambda = c/f$ = 3.0 × 10^{8} m/s ÷ 6.3 × 10^{14} Hz = **4.78 × 10^{-7} m** = 478 nm

The red light of 615 nm has too long a wavelength (too low a frequency) to cause photoelectrons to be ejected.

Alternative method:

$E = hc/\lambda$

= (6.63 × 10^{-34} J s × 3.0 × 10^{8} m s^{-1}) ÷ 615 × 10^{-9} m

= **3.23 × 10^{-19} J**

E = 3.23 × 10^{-19} J ÷ 1.6 × 10^{-19} J eV^{-1} = **2.02 eV**.

Photoelectrons will not be ejected as the photon energy is less than the work function.

3.02.5

(a) Work function is the amount of energy that is needed to remove a photoelectron from the metal

(b) The energy for each photon = 3.52×10^{-19} J = hf

$f = 3.52 \times 10^{-19}$ J ÷ 6.63×10^{-34} J s = **5.31×10^{14} Hz**

(c) Frequency: $f = c/\lambda = 3 \times 10^{8}$ m s^{-1} ÷ 400×10^{-9} m = 7.50×10^{14} Hz

$E_k = hf - \phi$ = (6.63×10^{-34} J s × 7.5×10^{14} Hz) - 3.52×10^{-19} J

$E_k = 4.97 \times 10^{-19}$ J - 3.52×10^{-19} J = 1.45×10^{-19} J

$v^2 = 2E_k/m$ = ($2 \times 1.45 \times 10^{-19}$ J) ÷ 9.11×10^{-31} kg = 3.18×10^{11} m^2 s^{-2}

v = **5.6×10^{5} m s^{-1}**

Tutorial 3.03

3.03.1

An electron is removed…

…by a collision with an electron…

…with at least the energy of the ionisation energy.

3.03.2

The electron is attracted by the electromagnetic force…

…because the charges are opposite.

When the electron interacts, it drops from the highest energy level…

…to the ground state,

…emitting a photon.

3.03.3

There are specific energy levels at which an electron can stay.

No other levels are possible.

As the electrons fall between these levels, a photon is emitted.

The photon frequency emitted depends on the difference between the levels.

The colour depends on the frequency of the photon.

3.03.4

Excited atom has an electron that is at a higher energy level…

…than the ground state.

Ionised atom has had the electron removed completely.

Tutorial 3.04

3.04.1

(a) It returns to its ground state, emitting photons.

(b) DE = -0.85 - -1.51 = 0.66 eV

$f = E/h$ = (0.66 eV × 1.6 × 10^{-19} J eV^{-1}) ÷ 6.63 × 10^{-34} J s = 1.593 × 10^{14} Hz

f = **1.6 × 10^{14} Hz** (2 s.f.)

3.04.2

(a) Hydrogen atom would be ionised…

…and the removed electron would have excess kinetic energy of 8.5 eV.

(b) The electron would be raised right to the ionisation point but would fall back to the ground state…

…emitting photons of specific wavelengths

(c) The photon would not be absorbed…

…Since there is no energy level 6.1 eV above the ground state.

3.04.3

ΔE = -3.41 eV - -13.6 eV = 10.19 eV

ΔE = 10.19 eV × 1.60 × 10^{-19} J eV^{-1} = 1.63 × 10^{-18} J

$f = \Delta E/h$ = 1.63 × 10^{-18} J ÷ 6.63 × 10^{-34} J s = 2.46 × 10^{15} Hz

$\lambda = c/f$ = 3.0 × 10^{8} m s^{-1} ÷ 2.46 × 10^{15} Hz = **1.22 × 10^{-7} m** = 122 nm.

This is UV light.

Tutorial 3.05

3.05.1

Electrons collide with mercury atoms...

...which are ionised.

The positive mercury atoms collect electrons...

.... which return to the ground state...

...emitting a UV photon.

The UV photon interacts with the fluorescent material around the tube.

The electrons are excited...

...and return to the ground state...

...emitting photons of visible light.

Tutorial 3.06

3.06.1

If waves have particle properties...

...then particles should behave like waves.

3.06.2

Radio waves diffracting over a hill.

Sound waves diffracting through a doorway.

3.06.3

Accelerated electrons...

...strike a carbon disc.

A diffraction pattern is formed.

Diffraction is a wave property.

3.06.4

$\lambda = h/p$ = 6.63 × 10^{-34} J s ÷ (9.11 × 10^{-31} kg × 2.0 × 10^{6} m s^{-1})

= 3.639 × 10^{-10} m = **3.6 × 10^{-10} m** (2 s.f.)

Tutorial 3.07

3.07.1

Ratio = 1.0 × 10^{5} Pa ÷ 10 × 10^{-6} Pa = 1 × 10^{10}.

The pressure from the atmosphere is **1 × 10^{10}** greater than the radiation pressure.

3.07.2

Formula:

$$F = \frac{P}{c}$$

F = 6.0 W ÷ 3.00 × 10^{8} m s^{-1}

F **= 2.0 × 10^{-8} N** = 20 nN

3.07.3

Formula:

$$p = \frac{I}{c}$$

p = 550 W m^{-2} ÷ 3.00 × 10^{8} m s^{-1}

p = **1.83 × 10^{-6} N**

3.07.4

The key to this is that mass can be considered to be energy and vice versa. This is summed up in the equation $E = mc^2$.

3.075

General relativity gives this equation:

$$E^2 = m^2c^4 + p^2c^2$$

If m = 0, this can be rewritten as:

$$E^2 = p^2c^2$$

Taking the square root:

$$E = pc$$

And rearrange to:

$$p = \frac{E}{c}$$

Where p is momentum.

From Newton II, we know that force is the rate of change of momentum:

$$F = \frac{\Delta p}{\Delta t}$$

Rearranging gives:

$$\Delta p = F\Delta t$$

Substituting gives us:

$$F\Delta t = \frac{E}{c}$$

And rearranging gives

$$F = \frac{E}{c\Delta t}$$

Since energy ÷ time gives power, we can write:

$$F = \frac{P}{c}$$

QED

3.07.6

(a) Work out energy per photon:

$$E = \frac{hc}{\lambda} = \frac{6.63 \times 10^{-34}\ \text{J s} \times 3.00 \times 10^{8}\ \text{ms}^{-1}}{122 \times 10^{-9}\ \text{m}} = 1.63 \times 10^{-18}\ \text{J}$$

There are 4 motors each of 10 kW. Total power = 4.0×10^4 J s^{-1} (Did you forget?)

Number of photons per second = 4.0×10^4 J s^{-1} ÷ 1.63×10^{-18} J = **2.45×10^{22} s^{-1}**

(b) Use:

$$F = \frac{P}{c}$$

F = 40000 W ÷ 3.00×10^8 m s^{-1} = **1.3×10^{-4} N**

(c) Use

$$a = \frac{F}{m}$$

a = 1.3×10^{-4} N ÷ 1500 kg

a = **8.7×10^{-8} m s^{-2}**

This acceleration is negligible; therefore, it's not a viable way to power a space probe.

Tutorial 3.08

3.08.1

The waves have the same phase relationship and have the same wavelength.

3.08.2

(a) Use:

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

ΔE = (6.63 × 10^{-34} Js × 3.00 × 10^{8} m s^{-1}) ÷ 620 × 10^{-9} m = 3.208 × 10^{-19} J

ΔE = 3.208 × 10^{-19} J ÷ 1.602 × 10^{-19} J eV^{-1} = **2.00 eV**

(b) E_2 = -15.6 eV + 2.00 eV = -13.6 eV

3.08.3

The excited atoms (i.e. with the electron in a raised energy state) outnumber the atoms at the ground state.

3.08.4

In a two-level system, the maximum number of excited electrons will be 50 %. Therefore, the LASER crystal will become optically transparent but will not gain sufficient energy to reach the LASER threshold.

Population inversion will not be achieved.

In a three-level system, there is a third high energy level to which electrons are raised (or pumped). There is a small transition that the electrons fall. This takes a very short time, so the electrons fall to the second level quickly, and the vast majority are found here.

The transition from the second level to the ground state has a long transition lifetime. Therefore, there are more excited electrons than the electrons at the ground state. Thus, there is population inversion which is required for stimulated emission.

3.08.5

(a) The wavelength is irrelevant. Although shorter wavelengths give rise to more energetic photons, there would be fewer photons per second for a given power.

(b) Intensity = power ÷ area

$A = \pi D^2/4 = (\pi \times (2.0 \times 10^{-3}\text{ m})^2) \div 4 = 3.14 \times 10^{-6}\text{ m}^2$

$I = 1.5 \times 10^{-3}\text{ W} \div 3.14 \times 10^{-6}\text{ m}^2 =$ **480 W m^{-2}** (This intensity is about the same as the intensity of light from the Sun on a bright spring day.)

(c) $p = I/c = 480\text{ W m}^{-2} \div 3.0 \times 10^{8}\text{ m s}^{-1} =$ **$1.6 \times 10^{-6}\text{ N m}^{-2}$**