CHAPTER 11

From the photoelectric effect to photo cells

The reconceptualisation of the model of light led to an understanding of the photoelectric effect and black body radiation

Introduction

Whether light is a wave or a stream of particles had scientists puzzled for centuries. While at times only a wave model can explain the behaviour of light, the photoelectric effect can only be explained with a particle model. This seemingly contradictory nature of light led to the development of a whole new way of thinking—quantum physics. The study of black body radiation and the photoelectric effect makes a fascinating story; it challenged the scientists of the time to leave behind old ways of explaining our world to one that would lead them a long way into the future.

11.1 Electromagnetic radiation (EMR)

- ***Identify the relationships between photon energy, frequency, speed of light and wavelength: $c = f\lambda$***

Definition

Electromagnetic radiation (EMR) consists of changing magnetic and electric fields that propagate perpendicularly to each other.

NOTE: EMR is also known as electromagnetic **waves**.

EMR exists in a number of different forms resulting from each one's unique frequency range, called wavebands. Some examples of EMR from the highest frequency to the lowest are: gamma rays, X-rays, ultraviolet (UV), visible light, infrared, microwaves, high-frequency radio waves and low-frequency radio waves. These comprise the **EMR spectrum**, which is summarised in Figure 11.1.

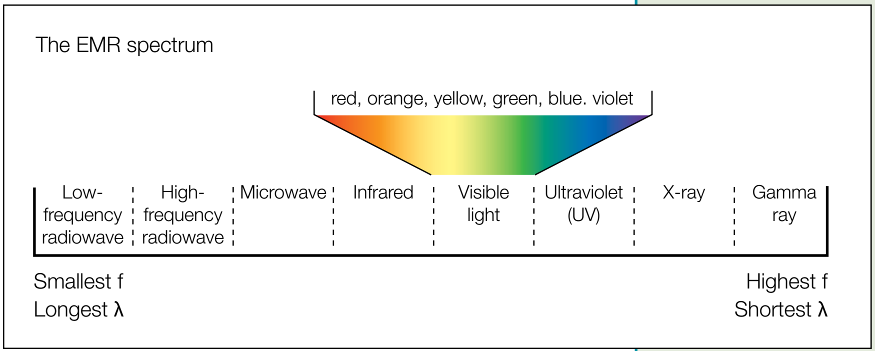

Figure 11.1 The EMR spectrum

At the same time, all EMR shares the common property that it can propagate through a vacuum and travels at a constant speed of approximately 3.0×10^8 m s^{-1}, that is c.

Relationship between frequency and wavelength

Recall from the preliminary course that the product of the frequency and wavelength of a wave equals its velocity. Mathematically:

$$v = f\lambda$$

Where:

v = the velocity of the wave, measured in m s^{-1}

f = the frequency of the wave, measured in Hz

λ = the wavelength of the wave, measured in m

In this context, since all EMR travels at the speed of light (c), v in the above equation is substituted with c; hence:

$$c = f\lambda$$

Where:

c = the speed at which light travels; it is a constant, which has a value of approximately 3.0×10^8 m s^{-1}

f = the frequency of the wave, measured in Hz

λ = the wavelength of the wave, measured in m

SR

Worked example 19

■ *Solve problems and analyse information using: $c = f\lambda$*

Example 1

A particular coloured light has a wavelength of 700 nm. What is its frequency?

Solution

$c = f\lambda$

$\lambda = 700 \times 10^{-9} = 7.00 \times 10^{-7}$ m

$$f = \frac{c}{\lambda} = \frac{3.0 \times 10^8}{7.00 \times 10^{-7}}$$

$f = 4.3 \times 10^{14}$ Hz

Example 2

Humans can see light frequencies ranging from 3.75×10^{14} Hz to 7.5×10^{14} Hz. What is the range of wavelengths humans can see?

Solution

$$c = f\lambda$$

when $f = 3.75 \times 10^{14}$ Hz

$$\lambda = \frac{c}{3.75 \times 10^{14}}$$

$$= \frac{3.0 \times 10^{8}}{3.75 \times 10^{14}}$$

$$= 8.0 \times 10^{-7} \text{ m}$$

when $f = 7.5 \times 10^{14}$ Hz

$$\lambda = \frac{c}{7.5 \times 10^{14}}$$

$$= 4.0 \times 10^{-7} \text{ m}$$

$\therefore$ the range of wavelengths humans can see is from 4.0×10^{-7} m to 8.0×10^{-7} m.

Example 3

In a red shift, it is observed that the frequency of EMR is decreased by 10%. By what percentage is its wavelength increased?

Solution

Let the original frequency be f and wavelength be λ; and the new frequency be f' and the new wavelength be λ':

Since $f\lambda = c$

$$f'\lambda' = c$$

$$\therefore f\lambda = f'\lambda'$$

Also $f' = f - 0.1f$ (10% = 0.1)

$$= f(0.9)$$

$$\therefore \cancel{f}\lambda = [\cancel{f}(0.9)] \cdot \lambda'$$

$$\lambda = \lambda'(0.9)$$

$$\lambda' = \frac{1}{0.9}\lambda$$

$$\lambda' \approx 1.11\lambda$$

$\therefore$ the new wavelength is 111% of the original wavelength; that is, it has increased by 11%

EMR and charged particles

As we have discussed, a stationary charge produces its own electric field, and a charge that is moving at a constant velocity produces a magnetic field. So what about accelerating charges? It is essential to remember:

An accelerating or oscillating charge produces EMR.

The reverse is also true:

EMR can cause charges to accelerate or oscillate.

PFA
H1

History of Physics: 'Evaluates how major advances in scientific understanding and technology have changed the direction or nature of scientific thinking'

TR

PFA scaffold H1
Mapping the PFAs

Hertz's discovery of radio waves and his measurement of their speed

■ ***Outlines qualitatively Hertz's experiments in measuring the speed of radio waves and how they relate to light waves***

Why was this discovery a major advance in scientific understanding?

At the time of Hertz's discovery, the scientific community had available to it James Clerk Maxwell's equations for EMR. These equations mathematically predicted the existence of other, unknown forms of EMR which should behave in similar ways to light, but differ in wavelength (and therefore frequency).

Hertz's discovery was the first of its kind to identify the nature of another form of EMR.

How did it change the direction or nature of scientific thinking?

Once Hertz had identified radio waves, which behaved as Maxwell's equations predicted, the search was on for yet other unidentified forms of EMR—UV, X-rays, microwaves (often referred to as a form of radio waves) and gamma rays, all of which were subsequently discovered. Within a few years, Hertz's radio waves were being put to use by Marconi for communication purposes.

Evaluation of Hertz's discovery of radio waves and measurement of their speed

Hertz's discovery was the first of many to verify the existence of what is now known as the electromagnetic spectrum. Maxwell's equations were shown to be correct. The many uses of the other forms of electromagnetism could then be developed. Thus Hertz's discovery was a profound step in this area of scientific research and endeavour. In honour of Hertz, the unit for frequency was named after the discoverer of radio waves.

WWW→

USEFUL WEBSITES

A short article containing photos of Hertz's apparatus:
http://www.sparkmuseum.com/BOOK_HERTZ.HTM

Articles that take one beyond Hertz's initial discovery:
http://www.britanica.net/nobelprize/article-25129

11.2 Hertz's experiment: production and reception of EMR

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Simulation: electromagnetic waves

■ ***Describe Hertz's observation of the effect of a radio wave on a receiver and the photoelectric effect he produced but failed to investigate***

German physicist Heinrich Hertz was the first person (1888) to conduct experiments to produce and investigate EMR after its existence was proposed by James Maxwell. Hertz was aiming to produce EMR other than visible light and determine its properties to see whether they agreed with Maxwell's early theoretical predictions. The experimental apparatus is schematically represented in Figure 11.2.

Heinrich Hertz

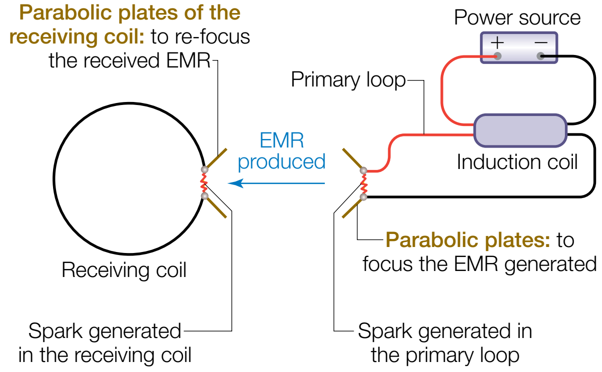


Figure 11.2 Hertz's experiment

NOTE: An induction coil (above) is used to step up the DC voltage. As discussed before, high voltage is required in order to allow the electrons to jump across the air gap. As electricity is conducted through the air, a spark is produced.

The procedure of Hertz's experiment

1. *Production of the EMR*: The current that was fed into the primary loop from the induction coil oscillated back and forth. This oscillation of charges (accelerating electrons) in the primary loop generated EMR (in this case a radio wave), which was emitted at the gap. There was also a spark generated across the gap as charges were conducted through the air.
2. *Transmission of the EMR*: The EMR (radio wave) was focused by the parabolic plates and travelled to the receiving coil.
3. *Reception of the EMR*: The EMR (radio wave) was again focused at the receiving coil. The EMR caused the electrons in the receiving coil to oscillate, thus regenerating the electric signal that was used in the primary loop, although much weaker. The oscillation of charges in the receiving coil also generated a spark across the air gap, although it was much fainter than the one in the primary loop due to the energy lost during transmission.

Measuring the speed of the EMR produced

■ *Outline qualitatively Hertz's experiments in measuring the speed of radio waves and how they relate to light waves*

Hertz was able to determine the speed of the EMR he produced by measuring its frequency and wavelength (since $v = f\lambda$). The frequency of the EMR must be identical to the frequency of the oscillation of the electric current, which could be predetermined. The wavelength was determined by taking measurements from the interference pattern generated by allowing the newly produced wave to take two slightly different pathways and recombining them at the receiving coil. Hertz calculated that the speed of the newly generated EMR was the same as that of light.

Other conclusions from the experiment

Not only did the newly produced EMR have the same speed as light, Hertz also showed that this radiation had all the other properties of light, such as reflection, refraction, interference and polarisation. Hence he concluded (and verified Maxwell's earlier prediction) that there exists a whole spectrum of EMR which all travel at the speed of light; the EMR he produced and light are just two out of many members of this spectrum.

One other important observation made by Hertz

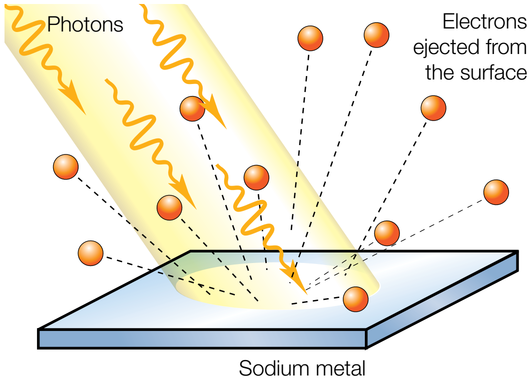
During his experiment, Hertz also observed that the intensity of the spark in the receiving coil faded considerably when the receiving coil was placed inside a dark box. To verify this, he also showed that by illuminating the receiving coil with a light source, a more intense spark was generated, with UV producing the most intense spark. Although Hertz recorded these experimental observations, he failed to further investigate this 'mysterious' phenomenon.

It was found later that what Hertz had observed was the phenomenon known as the **photoelectric effect**. So what is the photoelectric effect?

11.3 The photoelectric effect

Definition

The **photoelectric effect** is the phenomenon that a metal surface emits electrons when struck by EMR with a frequency above a certain value.



The photoelectric effect

Consider the following example:

Example 1

Two electroscopes are set up. One is charged negatively and the other positively, so that their leaves are widely separated. Each electroscope has a piece of pure

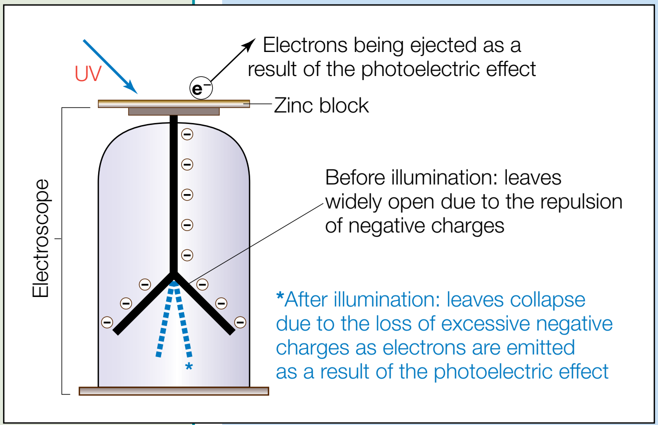


Figure 11.3 (a) A negatively charged electrode illuminated by UV

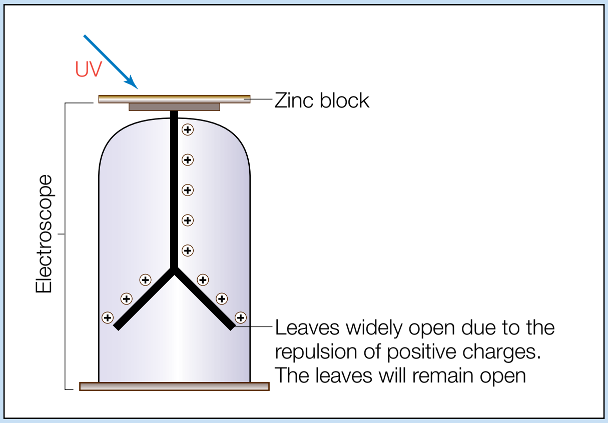


Figure 11.3 (b) A positively charged electroscope illuminated by UV

zinc placed on its top. When a UV lamp is used to illuminate the zinc metal, the leaves of the negatively charged electroscope collapse very quickly, whereas the leaves of the positively charged electroscope remain almost unaltered. Account for what happened.

Solution

When the UV lamp illuminates the negative electroscope, the UV light has enough energy to cause the zinc metal, hence the electroscope, to emit free electrons—the photoelectric effect (see Fig. 11.3a). As the excessive negative charges on the leaves are dissipated quickly by the release of the electrons, the leaves of this electroscope collapse very rapidly.

On the other hand, for the positive electroscope, UV light does not have sufficient energy to free electrons from an already positively charged surface (due to electrostatic attraction). Hence the position of the leaves remains almost unaltered (see Fig. 11.3b).

NOTE: Even if the photoelectric effect did take place in this case, losing electrons from a positively charged electroscope would not help to collapse the leaves but would open them even wider.

Explanation for Hertz's observation

So how can we use the photoelectric effect to account for Hertz's observation?

When the receiving coil is illuminated by UV free electrons are emitted at the terminal of the receiving coil as a result of the photoelectric effect. Once freed, these electrons can be much more readily accelerated back and forth in the air gap by the voltage generated in the receiving coil, resulting in a stronger spark at the receiving coil. Placing the receiving coil inside a dark box means the UV light is blocked; hence, the photoelectric effect cannot occur. Consequently, significantly fewer free electrons are released and accelerated across the gap in the receiving coil, thus the spark is fainter.

Illuminating the gap of the receiving coil with light facilitates the photoelectric effect, increasing the intensity of the spark. It is now known that while UV light can cause the photoelectric effect, visible light or other EMR with frequencies less than that of UV light do not have enough energy to cause the photoelectric effect (See later sections). Thus not surprisingly, UV light produces the most intense spark.

More about the photoelectric effect

After the photoelectric effect was discovered, many experiments were carried out to demonstrate its properties. Some results are:

1. The photoelectric effect only happens if the EMR used has a frequency above a certain value.
2. The maximum kinetic energy of the photoelectrons emitted depends on the frequency of the EMR used, not its intensity.

NOTE: Photoelectrons refer to the electrons released as a result of photoelectric effect.

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Animation: the photoelectric effect

3. Once the right frequency is achieved, emission of photoelectrons is instantaneous. If this frequency is not achieved, no matter how long a metal surface is illuminated, no photoelectrons will be emitted.
4. An increase in the intensity of the EMR used will result a larger **photocurrent**.

NOTE: Photocurrent refers to current resulting from moving photoelectrons.

Based on classical physics, scientists at the time could not offer any satisfactory theoretical explanation for these experimental observations.

NOTE: Classical physics means traditional physics: this term is further explained in the next section.

Thus before we can offer a satisfactory explanation for the photoelectric effect, we must first examine a new area of physics, known as **quantum physics**.

11.4 Quantum physics

Classical physics is traditional physics, which relies heavily on the contributions made by Isaac Newton, so it is sometimes called Newtonian physics. In such physics, all quantities are considered to be continuous and can take any value within a certain range. Classical physics is useful in describing macroscopic physical phenomena, such as the motion of a satellite or the torque of a motor.

Quantum physics was introduced at the end of the 19th century. In quantum physics, quantities are considered to have discrete or non-continuous values, and have a limited number of values that they can take. Quantum physics is essential in describing microscopic physical phenomena, such as the photoelectric effect, energy levels of electrons, properties of a nucleus, and so on. (For more on quantum physics, please refer to From Quanta to Quarks.)

Which physics theory is correct? The answer is that they are both correct, as they are theories proposed to explain certain phenomena in certain situations. It is more correct to identity one as the supplement to the other.

Black body radiation is a good example of quantum physics.

11.5 Black body radiation and the black body radiation curve

- ***Identify Planck's hypothesis that radiation emitted and absorbed by the walls of a black body cavity is quantised***
- ***Identify the relationships between photon energy, frequency, speed of light and wavelength: $E = hf$***

Definition

A **black body** need not be 'black', rather, by definition, a black body is an object that can absorb and/or emit energy perfectly.

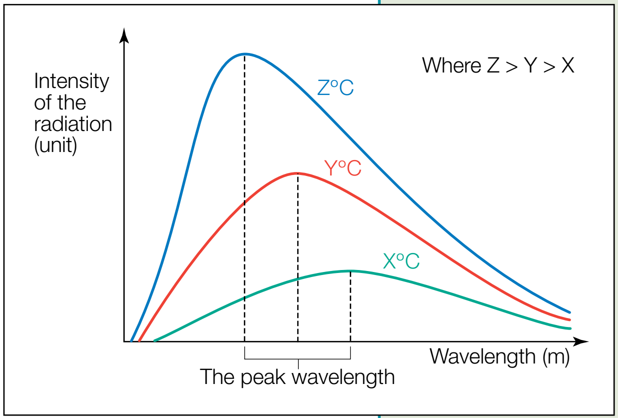


Figure 11.4 Three black body radiation curves

A piece of tungsten metal can behave as a perfect black body. The Earth itself is almost a perfect black body, taking energy from the Sun and emitting energy back into space. A star is yet another example of a non-perfect black body.

When a black body is heated to some temperature in a vacuum, for example, by electric heating, it starts to emit radiation perfectly, known as **black body radiation**. This radiation can cover the entire range of the EMR spectrum with the intensity varying with the wavelength. If the individual wavelengths of this radiation are detected and the corresponding intensities measured experimentally, the data can then be plotted as 'intensity' versus 'wavelength', to produce a **black body radiation curve**.

Black body being heated

Three black body radiation curves are shown in Figure 11.4, each obtained by heating the black body to a specific temperature:

A few important trends need to be emphasised here for the black body radiation curves:

- The black body radiation curve for a given temperature will have a peak, which represents the wavelength with the highest intensity.
- When the temperature is increased, the height of the entire curve is increased. It is also important to note that the position of the peak is also shifted towards smaller wavelengths (higher frequencies). This explains why a cool star emits mostly infrared and appears reddish, whereas a very hot star emits mostly UV and appears blue.

The 'UV catastrophe', or 'left-hand catastrophe'

The black body radiation curves shown in Figure 11.4 are obtained empirically by plotting experimental measurements. However, when scientists at the time tried to apply mathematics to the black body radiation in an attempt to derive the black body radiation curve theoretically, they found inconsistencies. The right-hand side of the curve agreed with the one derived experimentally. However, the theoretical curve had no peak, rather it approached infinity as the graph approached small wavelengths (high frequencies) (see Fig. 11.5). This is known as the 'UV catastrophe'.

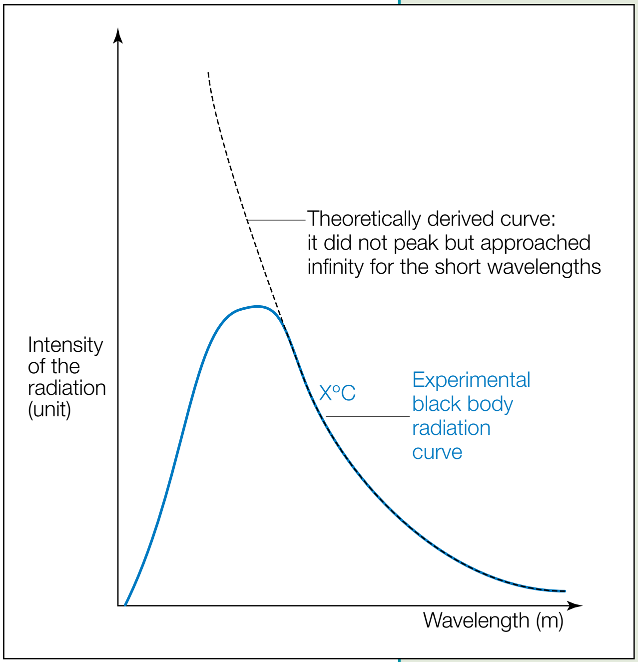
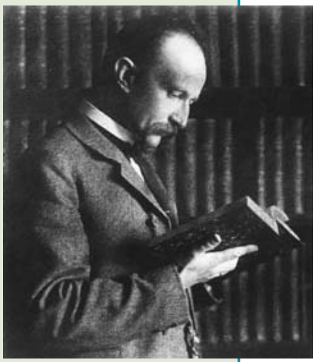


Figure 11.5 The UV catastrophe

The revolutionary quantum hypothesis by Max Planck

To help to theoretically derive the black body radiation curve, German scientist Max Planck


Max Planck

proposed a radical hypothesis, known as Planck's hypothesis of black body radiation, which states:

The radiation emitted from a black body is not continuous as waves—it is emitted as packets of energy called quanta (photons).

The energy of these quanta or photons are related to their frequencies by the equation:

$$E = hf$$

Where:

E = the energy of each quantum or photon, measured in J

h = Planck's constant, with a value of 6.626×10^{-34} J s

f = the frequency of the radiation, measured in Hz

Planck's quantum hypothesis for black body radiation was revolutionary; he simply proposed this hypothesis in order to mathematically derive the black body radiation curve. The proposal violated many physical laws of the time, and thus was not well supported by the scientific community. Even Planck himself was not convinced his hypothesis was correct.

NOTE: Planck's hypothesis led to the idea that energy is quantised, which is widely accepted today and also forms the basis of modern quantum physics.

■ *Solve problems and analyse information using E = hf*

Example 1

A particular light wave has a wavelength of 420 nm. What is the energy of each of its photons?

Solution

$$E = hf$$

$$h = 6.626 \times 10^{-34} \text{ J s}$$

$$c = f\lambda$$

$$f = \frac{c}{\lambda} = \frac{3.0 \times 10^{8}}{4.2 \times 10^{-7}} \approx 7.14 \times 10^{14} \text{ Hz}$$

$$\therefore E = (6.626 \times 10^{-34}) \times (7.14 \times 10^{14})$$

$$\approx 4.73 \times 10^{-19} \text{ J}$$

Example 2

If the frequency of an AM radio wave is 1000 kHz, what will be the energy of each photon?

Solution

$$E = hf$$
$$h = 6.626 \times 10^{-34} \text{ J s}$$
$$f = 1000 \times 1000 = 10^6 \text{ Hz}$$
$$\therefore E = (6.626 \times 10^{-34}) \times (10^6)$$
$$E = 6.626 \times 10^{-28} \text{ J}$$

Particle nature of light

11.6

SR

Simulation: models of light: electromagnetic spectrum

■ *Explain the particle model of light in terms of photons with particular energy and frequency*

From our previous study, we have learnt that light can be reflected, refracted, deflected, interfered and polarised, which undoubtedly proves light is a transverse wave. However, based on the quantum hypothesis proposed by Planck, the energy of light is quantised and comes as packets; this suggests light is composed of particles.

This phenomenon, whereby light can behave as both waves and particles at the same time, is known as the **wave-particle duality** of light. (This idea can also be generalised for other matters, see From Quanta to Quarks.)

Each light particle, or **photon**, possesses an amount of energy related to the frequency of the light wave, as described by the equation: $E = hf$.

NOTE: Many students wonder how light can be particles and waves at the same time—which one is more correct? The answer is that both are correct. Generally, it is important to throw away one's common sense in dealing with abstract concepts like this. Whether light is waves or particles, they are both models we created that apply to certain situations but not others. When we deal with reflection and refraction, light is a wave; when we deal with the photoelectric effect (see below) or the fact that light can be influenced by gravity, light is particles. These two models certainly do not conflict with each other; rather they work conjointly to allow us to describe all the behaviours of light.

Einstein's explanation for the photoelectric effect: a quantum physics approach

11.7

■ *Identify Einstein's contribution to quantum theory and its relation to black body radiation*

As mentioned before, the phenomenon of the photoelectric effect cannot be explained by classical physics. In 1905, Albert Einstein combined Planck's hypothesis that the energy of radiation was quantised and the particle model of light to explain the photoelectric effect, as follows:

1. Light behaves like particles called photons, each carries a discrete package of energy. The energy of the photon is related to its frequency by $E = hf$. The collisions between photons and electrons lead to the photoelectric effect.
2. Only photons with energy above the **work function** (W) of a metal can cause the photoelectric effect. The work function is defined to be the minimum energy required to free electrons from the metal surface, and is different for different metals. The minimum frequency (which detemines the energy) the light must have to cause the photoelectric effect in a metal is called the **threshold frequency** for that metal. The kinetic energy of the photoelectrons released is determined by the difference between the energy of the photon (hf) and the work function (W) of the metal: $E_k = hf - W$.
3. A photon can transfer either all of its energy to an electron, or none. If the frequency of the photon is less than the threshold frequency, its energy, even if transferred to an electron, will not be sufficient for the electron to leave the surface.

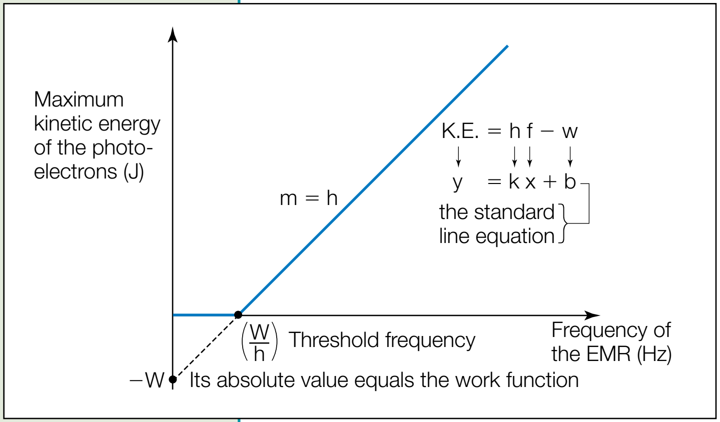


Figure 11.6
Kinetic energy of the photoelectrons versus frequency of the illuminating EMR

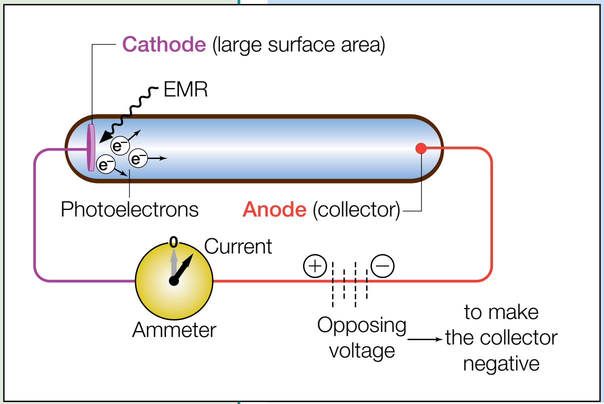
A graphic analysis

Plotting the maximum kinetic energies of photoelectrons emitted against the frequencies of the illuminating EMR for one particular metal surface (a fixed work function), will result in a graph like that shown in Figure 11.6.

A few important features of the graph need to be emphasised:

- The **slope** of the graph is equal to Planck's constant *h*. If graphs are drawn for other metals with different work functions, all those graphs will be parallel to each other, as they all share the same slope *h*.
- The ***x*-intercept** of the graph is equal to the threshold frequency. If a metal with a larger work function is used, this point shifts to the right, indicating that a higher threshold frequency is required.
- The absolute value of the ***y*-intercept** of the graph is equal to the work function of the metal. If a metal with a larger work function is used, then the *y*-intercept shifts downwards.

Figure 11.7
Measuring the kinetic energy of photoelectrons



Example

When light with a frequency greater than the threshold frequency shines on a photoelectric cathode embedded in an evacuated tube, electrons will be emitted as expected (see Fig. 11.7). ('Photoelectric' refers to a material that readily undergoes photoelectric effect to release electrons.) These electrons will have a specific amount of maximum kinetic energy and in this case will move away from the cathode across the vacuum tube to reach the collector. This causes a photoelectric current to flow.

One way of actually measuring the kinetic energy of the photoelectrons experimentally is by making the collector negative enough to repel the photoelectrons to prevent them from reaching the collector. This can be done by inserting a power source into the circuit with the correct orientation, as shown by the dashed lines in Figure 11.7. The consequence of this is that the photocurrent in this circuit drops to zero. The minimum voltage the power source needs to supply in order to make this happen is known as the **stopping voltage**. The stopping voltage correlates directly with the kinetic energy of the photoelectrons; a larger stopping voltage means more work needs to be done to stop the photoelectrons reaching the collector, which in turn reflects higher kinetic energies.

(a) Suppose the incident EMR has a wavelength of 350 nm and the photoelectric cathode has a work function of 4.53×10^{-19} J; calculate the maximum kinetic energy for the photoelectrons released.

(b) Find the maximum velocity of these photoelectrons.

(c) How big should the stopping voltage be in this case?

Solution

(a)

$$E_k = hf - W$$

$$h = 6.626 \times 10^{-34}$$

$$f = \frac{c}{\lambda} = \frac{3.0 \times 10^8}{3.5 \times 10^{-7}} \approx 8.57 \times 10^{14}\ \text{Hz}$$

$$W = 4.53 \times 10^{-19}\ \text{J}$$

$$\therefore E_k = (6.626 \times 10^{-34}) \times (8.57 \times 10^{14}) - 4.53 \times 10^{-19}$$

$$\approx 1.15 \times 10^{-19}\ \text{J}$$

(b) The kinetic energy of these photoelectrons is related to their velocity by the equation:

$$E_k = \tfrac{1}{2} m\boldsymbol{v}^2$$

$$E_k = 1.15 \times 10^{-19}\ \text{J}$$

$$m = \text{mass of the electron} = 9.109 \times 10^{-31}\ \text{kg}$$

$$\therefore \boldsymbol{v} = \sqrt{\frac{2E_k}{m}}$$

$$= \sqrt{\frac{2 \times (1.15 \times 10^{-19})}{9.109 \times 10^{-31}}} = 5.02 \times 10^5\ \text{m s}^{-1}$$

(c) In order to stop the photoelectrons reaching the collector, the power source must apply an opposing energy (work) that is at least equal to the kinetic energy of these photoelectrons. The work done by any electric system can be defined as the product of the voltage and charge, that is, ($W = qV$). Hence:

$$E_k = \text{Work}_{\text{opposing}} = qV_{stop}$$

$$E_k = 1.15 \times 10^{-19}\ \text{J}$$

$$q = \text{charge of the electrons}$$

$$= 1.602 \times 10^{-19}\ C\ \text{(negative)}$$

$$\therefore V_{stop} = \frac{E_k}{q}$$

$$= \frac{1.15 \times 10^{-19}}{1.602 \times 10^{-19}}$$

$$V_{stop} = 0.72\ \text{V}$$

NOTE: If V_{stop} is known (measured) then the kinetic energy of the photoelectrons can be determined experimentally.

11.8 Using Einstein's explanation to investigate the photoelectric effect

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Simulation: the photoelectric effect

In section 11.3 (page 196) we listed some properties of the photoelectric effect and, as mentioned in the same section, these properties **cannot** be explained by classical physics. However, it is easy to explain them using Einstein's quantum mechanical approach.

Most of the answers lie in Einstein's equation: $E_k = hf - W$. In order for the photoelectric effect to take place, hf needs to be larger than W (in order to make E_k positive); since h is a constant, it follows that f needs to be above a certain value. Once photoelectrons are emitted, what determines their kinetic energy is the frequency of the incident EMR and the value of the work function. Since intensity is not part of the equation, it plays no role in determining the kinetic energy of the photoelectrons.

The **all or none principle** also has its own important consequences. If the photons have the right energy (thus frequency) to cause a photoelectric effect, they may transfer all their energy instantaneously, so emission of the photoelectrons is instantaneous. However, if the photons have insufficient energy, then no energy is transferred. This effectively means there is no accumulation of the energy level of the electrons. Consequently no matter how long they are illuminated by the photons, their energy will never exceed the threshold value to cause a photoelectric effect.

Although **intensity** has no effect on the kinetic energy, it does determine the number of photoelectrons released per unit time, if the frequency is above the threshold value. This is because intensity is a measure of how many photons are received per unit time. Higher intensity means more photons are bombarding the electrons, which means more photoelectrons are emitted. Since current is defined as the number of charges passing through a point in a second (recall: $I = \frac{q}{t}$), the more photoelectrons, the higher the current.

NOTE: However, it is important to note that if the frequency is below the threshold frequency, then the intensity has no influence on the photoelectric effect.

11.9 Einstein's contributions to quantum physics and black body radiation

H12.3A, B, D
H13.1A, B, C

PFA H1

PFA H2

- ***Identify data sources, gather, process and analyse information and use available evidence to assess Einstein's contribution to quantum theory and its relation to black body radiation***

Planck is believed to have been the initiator of quantum physics. When Planck first proposed the idea of the quantisation of energy, it was thought to be radical and even Planck himself could not be convinced that this was true. However, when Einstein 'borrowed' this idea and used it to successfully explain the photoelectric effect, it provided convincing evidence to back up this radical hypothesis. Einstein's idea of the quantisation of the energy of light led many scientists at the time to realise there was a whole new area of physics opening up.

Later, when Millikan performed his experiment to analyse the relationship between the frequencies of the incident EMR and the kinetic energies of the photoelectrons released by different metal surfaces, he plotted them as shown in Figure 11.6. Not only he was able to verify Einstein's equation for the photoelectric effect, he was also able to determine a more precise value for *h* by examining the gradient of the line. This was the first time Planck's constant *h* could be derived experimentally. Before that, the value for *h* could only be determined empirically by fitting the mathematically derived black body radiation curve with the one obtained experimentally (in other words, by trial and error). This further strengthened the connection between the photoelectric effect, the black body radiation curve and Planck's hypothesis, which form the heart of quantum physics.

Applications of the photoelectric effect: the implementation

SECONDARY SOURCE INVESTIGATION

PFAs

H3

PHYSICS SKILLS

H12.3A, D
H13.1A, B, C, D, E
H14.1G

- ***Identify data sources, gather, process and present information to summarise the use of the photoelectric effect in:***
  - ***photocells***
- ***Identify data sources, gather, process and present information to summarise the effect of light on semiconductors in solar cells***

We turn to the implementation part of the photoelectric effect. Two devices will be examined: photocells and photovoltaic (solar) cells.

Photocells

Definition

Photocells are electronic devices with resistances that alter in the presence of light.

A fundamental photocell, called a phototube, consists of a low-pressure glass bulb, in which is embedded an anode and a large cathode coated with a photoelectric material. Figure 11.8 shows a schematic representation of a phototube.

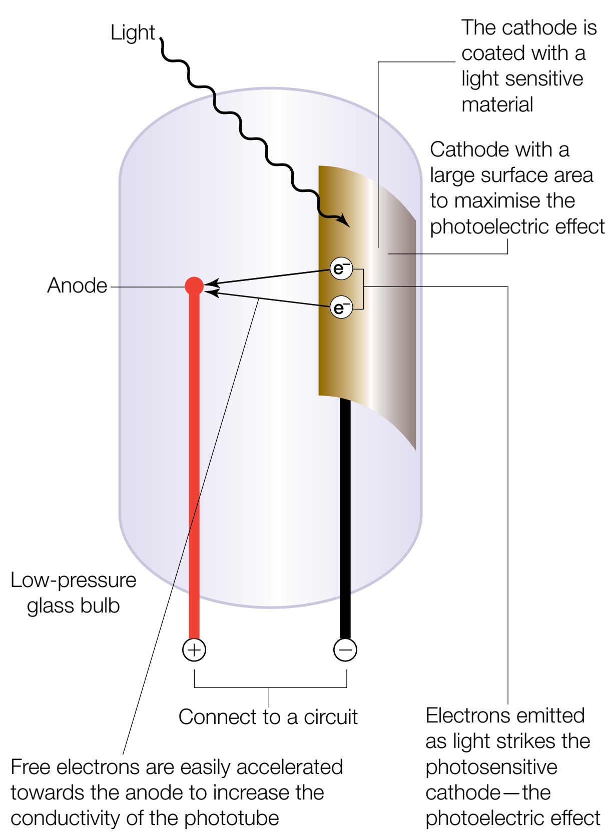
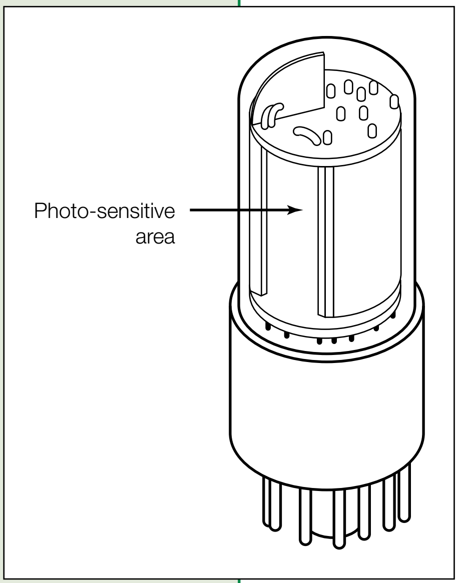


Figure 11.8 The structure of a phototube

Functional principle

When a photocell is connected to a circuit, the gap between the cathode and anode means that the resistance it



A phototube

Automatic doors

develops is infinite, consequently no current can flow in the circuit despite there being a supplied voltage.

When a light shines on the light sensitive cathode, electrons are emitted as a result of photoelectric effect. These free electrons can conduct electricity quite easily from the cathode to the anode, which consequently lowers the resistance of the photocell. As a result, a current starts to flow in the circuit. This current then triggers another functional system such as an alarm, usually through an amplifying electric circuit.

Common uses of photocells

Generally, photocells are used when electronic circuits need to be switched on or off by lights. Some examples include:

- **Alarm systems in houses:** For instance, thieves break into a house and turn on the lights, which triggers the photocell and causes the alarm to sound.
- **Automatic doors:** Infrared light emitted from the sensor is reflected from the approaching objects and triggers the photocell, which then controls the opening of the doors.
- **Door alarms for shops**, which beep when customers come into the shop.

Photovoltaic (solar) cells

These are discussed in Chapter 12, along with semiconductors and solid state devices.

Can science be set free from social and political influences? Einstein and Planck's views

SECONDARY SOURCE INVESTIGATION

PFAs

H1

- ***Process information to discuss Einstein and Planck's differing views about whether science research is removed from social and political forces***

NOTE: Neither Einstein nor Planck made any personal statements that could answer the above question. It is therefore necessary to examine their life stories and reach an answer based on each person's contributions, both scientifically and socially.

Einstein and Planck were contemporaries and they were also friends. However, their very different socio-economic backgrounds and personalities led to their distinct views on the relationship between science and politics.

Einstein

Einstein is considered one of the greatest physicists who ever lived. His special theory of relativity (discussed in Chapter 4) and general relativity (not required by the syllabus), and his investigation into the photoelectric effect all had profound impacts on the way humans perceive the Universe.

Not only did he devote his life to physics, he was also a strong believer in pacifism—he opposed wars and violence. Indeed he spent just as much time studying and preaching pacifism as he did in physics research.

Einstein was a politically active man. He openly criticised German militarism during World War I. After World War I, he constantly moved around the world to give lectures on physics and more importantly to preach his pacifist ideals and promote peace for the world. However, an irony of his later life, after he emigrated to the US (at the beginning of World War II), was the famous letter he wrote to the US president, Franklin Roosevelt, to convince him to set up the project of making nuclear bombs (later to be known as the 'Manhattan Project'), which later led to the deaths of tens of thousands of people in Japan. His rationale was his fear that the Germans were developing nuclear technology and might build nuclear bombs first. When Einstein realised after the war that the Germans were nowhere near making nuclear bombs, he painfully regretted his decision.

Indeed, Einstein's famous equation $E = mc^2$ (see Chapters 4 and 16) made him inseparable from society and politics, as this physics knowledge resulted in the creation of the most powerful and deadly weapon ever known to humankind. This also served as the basis for the development and implementation of nuclear power stations.

Planck

While Einstein came from a Jewish working-class family, Planck came from an upper-class German family.

His famous quantum theory made him the authority in German physics. Unlike Einstein, Planck continued his physics research at the University of Berlin under the Nazi regime during World War II. He was not as politically active as Einstein and focused on his physics research even during the war.

However, Planck was not amoral. He did go to Adolf Hitler in an attempt to stop his racial policies. It could be argued that this was an act guided by his moral values; it could also be argued he did this simply to preserve the development of German physics, with no intention of influencing political decisions.

The production of radio waves

FIRST-HAND INVESTIGATION

PFAs

H1

PHYSICS SKILLS

H12.1A, B, D
H12.2A

- ***Perform an investigation to demonstrate the production and reception of radio waves***

Demonstrate the production and reception of radio waves

This is a relatively simple experiment. The apparatus may be set up in a similar way to Hertz's experiment described early in this chapter. A spark in the receiving loop may be observed if the laboratory is dark enough. However, it is rather difficult to measure the speed or determine the properties of these radio waves experimentally in school labs.

If a spark cannot be seen in the receiving loop, the radio wave produced can be heard as a buzzing sound by


The equipment used

TR

Risk assessment matrix

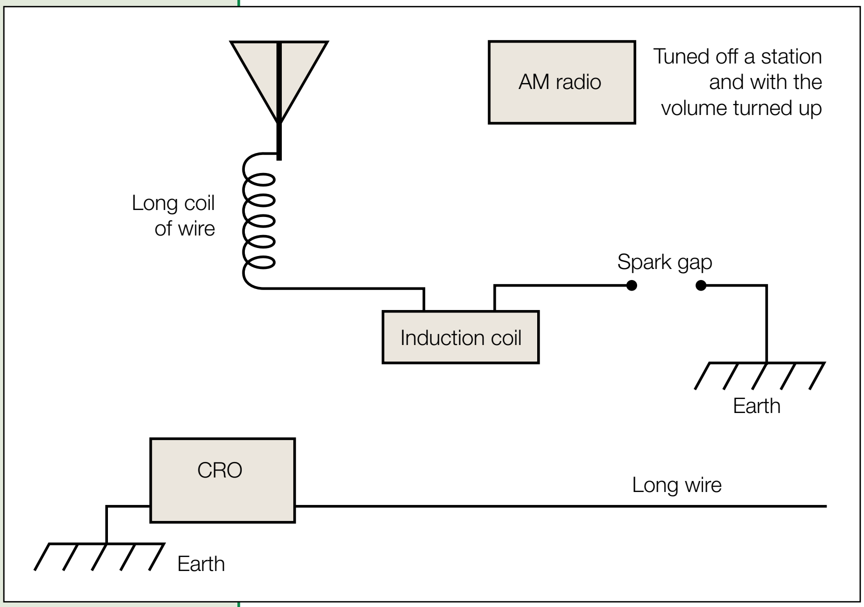


Figure 11.9 An alternative method of demonstrating the production and receiving of a radio wave

using a piezoelectric ear piece (such as one made from quartz) from an old-fashioned radio. This is because the radio waves produced cause the piezoelectric material in the ear piece to vibrate, thus generating a buzzing sound.

Alternative method

Radio waves are also produced by sparks. Lightning produces radio waves that can interfere with radio reception. Sparks from an induction coil produce radio waves that can be received by any AM radio placed within a few metres of the coil. The static noise can be heard in time with the sparking.

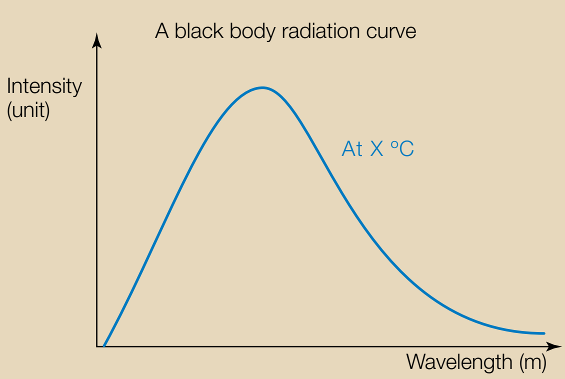
It can be observed that the radio static is not as pronounced on FM radio, which is one of the many benefits of FM radio broadcasts.

Figure 11.9 shows a schematic diagram of the apparatus that can be used for this investigation. Extreme care needs to be taken with the induction coil due to the high voltage and X-rays produced.

A second AM radio tuned off a station by about 500 Hz from the other radio and with the volume turned down can help you hear the other one. (It will act as an oscillator and with a bit of fiddling produce a 'tone'.)

CHAPTER REVISION QUESTIONS

1. Describe the purpose of Hertz's experiment involving radio waves. What was the other significant observation made by Hertz during this experiment?
2. Describe the fundamental differences between classical Newtonian physics and quantum physics.
3. The following sketch is a black body radiation curve.



(a) How can a black body radiation curve be obtained experimentally?

(b) Sketch another curve using the same axis, at a temperature Y °C, where Y is greater than X.

4. Define Planck's hypothesis. Under what circumstances was this hypothesis made?

5. Calculate the energy of the photons of:
(a) A radio wave that has a wavelength of 50 cm.
(b) An X-ray that has a wavelength of 1.1×10^{-10} m.

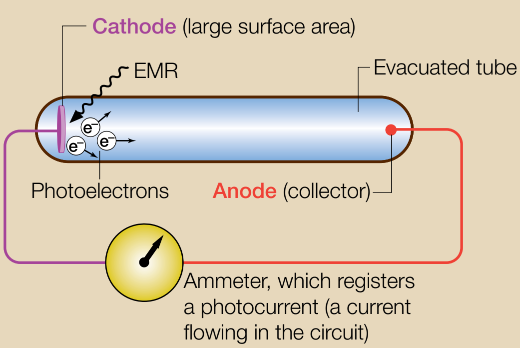
6. A very dim light beam has 270 photons passing through a given point in one second. If this beam of light is rated as 2.23×10^{-16} W, calculate the frequency of this light beam.

7. Can the photoelectric effect take place with an insulator? Justify your answer.

8. Einstein won the Nobel Prize for his contributions to the photoelectric effect. Analyse Einstein's explanation for the photoelectric effect; make specific reference to the quantum theory.

9. Describe the effect of intensity of the incident EMR on the maximum kinetic energy of the photoelectrons released.

10. An evacuated glass tube with a photoelectric cathode is set up as shown in the diagram. When light shines on this cathode, electrons are emitted. Light with different frequencies is used.



(a) The table below records the frequency of the incident EMR and the kinetic energy of the photoelectrons. Plot them on a graph using appropriate axes.

TR

Graph paper

Frequency of the incident EMR (Hz)	Kinetic energy of the photoelectrons (J)
1.0×10^{14}	0
3.0×10^{14}	8.18×10^{-20} J
5.0×10^{14}	2.14×10^{-19} J
7.0×10^{14}	3.47×10^{-19} J
9.0×10^{14}	4.79×10^{-19} J

(b) Describe the meaning of the *x*- and *y*-intercept and the gradient of the graph. Use the graph to determine the work function of the metal used as the photoelectric cathode.
(c) Friends of yours argue that they can just use one set (row) of data in the table to calculate the work function of this metal. They insist this will save a lot of time. Critically explain to them why the method you employed in part (b) is superior.
(d) In order to measure the kinetic energy of these photoelectrons, scientists would have to apply an opposing voltage (called the stopping voltage) to stop these photoelectrons, so that the net current flowing in the circuit would be zero. How

should such a voltage source be placed in this circuit, and what is the stopping voltage for each of the above frequencies?
(e) On the same axes used in part (b), sketch the graph for another metal with a lower work function.

11. The operation of old-fashioned breathalysers involves applications of the photoelectric effect.
(a) Initially, the analyser contains dichromate solution, which is orange in colour. This filters the white light in the system to produce an orange light beam. This orange light then shines on to the detector, which is effectively a photocell. If the orange light has a wavelength of approximately 620 nm, calculate the energy of photons as received by the detector.
(b) These orange photons are not energetic enough to cause photoelectric effect in the photocell. However, when alcohol is breathed into the solution (from the driver's mouth who has been drinking), it changes the dichromate to chromium oxide, which turns the solution green. This changes the initial orange light beam into a green light beam. Calculate the energy of the green photons, if green light has a wavelength of approximately 520 nm.
(c) Green light is energetic enough to cause a photoelectric effect in the photocell (detector). Estimate the size of the work function of the cathodic plate of the photocell.
(d) Based on the information above and the knowledge about how photocells work, suggest how a breath analyser can help to identify whether a particular driver has been drinking or not.

12. As part of your HSC course, you should have tried to demonstrate the production and reception of radio waves.
(a) Describe the set-up you used to produce radio waves.
(b) Identify a simple procedure you may use to confirm that radio waves have been produced.

SR

Answers to chapter revision questions

13. What was Einstein's view of the relationship between science and politics? What evidence is there for this view?