CHAPTER 7

Quantum Physics

How did the idea of the quantum theory arise?

What is the meaning of quantum energy and photon?

What is wave-particle duality?

What are the characteristics of photoelectric effect?

You will learn:

- **7.1** The Quantum Theory of Light
- **7.2** The Photoelectric Effect
- **7.3** Einstein's Photoelectric Theory

Learning Standards and List of Formulae in Chapter 7

Information Portal

The understanding of properties and behaviours of matter in the atomic scale enables quantum computers to be invented. Quantum computers are supercomputers that can process large amounts of information in a very short time. For example, complex chemical reactions can be quickly simulated to enable the building of a chemical reaction model. This technology can be applied in astronomy and the stock market. This is because the mechanism behind astronomical phenomena is complex, while stock market changes rapidly. Thus, the development of detailed models by supercomputers helps us to understand complex phenomena and make appropriate decisions.

https://bit.ly/3j7WZdV

Importance of the Chapter

The understanding of quantum physics helps researchers to create sophisticated computer systems with large memory and very high processing speed. The development of these inventions can propel competent and dynamic experts and physicists to respond to the increasingly challenging quantum era.

Futuristic Lens

The encryption process is essential to ensure the security and confidentiality of information of an organisation, financial institution or government. Knowledge in quantum physics allows the development of a more secure encryption algorithm system and a new digital signature.

https://bit.ly/2Eprehr

7.1 Quantum Theory of Light

In Form 4, you learned that the electromagnetic spectrum is a continuous spectrum. This spectrum consists of seven types of waves with different frequencies and wavelengths as shown in Figure 7.1.

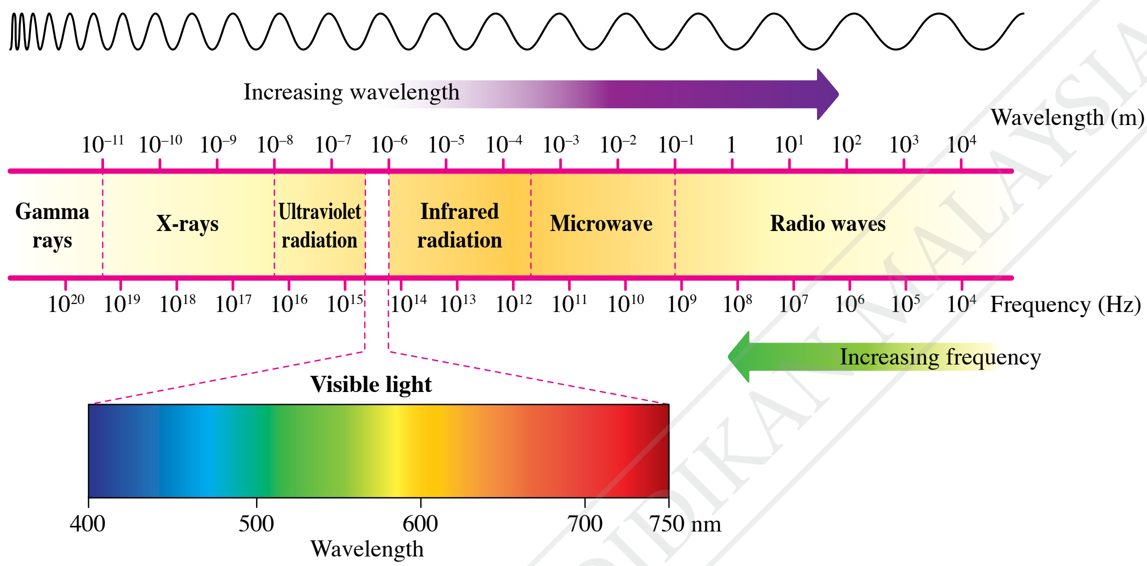


Figure 7.1 *Electromagnetic spectrum*

All objects emit electromagnetic radiation. Cold objects emit waves with low frequencies, such as radio waves or microwave, while hot objects emit waves with higher frequency, such as visible light and ultraviolet radiation. Do humans also emit electromagnetic radiation?

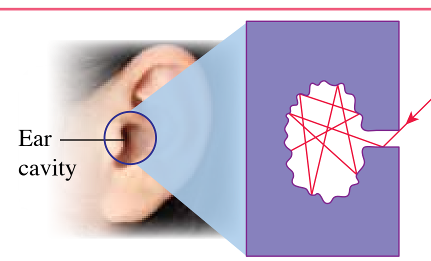
A **black body** is an idealised body that is able to absorb all electromagnetic radiation that falls on it. A black body can also emit thermal radiation depending on its temperature. The radiation emitted forms a continuous spectrum and is unaffected by the nature of the black body surface. Thus, an object emitting electromagnetic radiation which is determined by its temperature is known as a black body radiator.

Info GALLERY

Thermal radiation is electromagnetic radiation that includes visible light and radiation that cannot be seen by the human eye such as infrared radiation.

Info GALLERY

The rays of light that enter the ear cavity will undergo repeated reflections on the inner walls of the ear cavity. At each reflection, parts of the rays are absorbed by the inner walls of the ear until all the rays are absorbed. Thus, the ear cavity acts like a black body.



As the temperature of an object rises, the object acts as a black body radiator and emits thermal radiation of all wavelengths. Figure 7.2 shows a graph of radiation intensity against wavelengths of three types of black bodies at different temperatures. Usually, every curved graph of the black body spectrum is narrower on its left, which is an area with short wavelengths and high frequencies. With increasing temperatures, the wavelength approaching maximum radiation intensity will also get shorter.

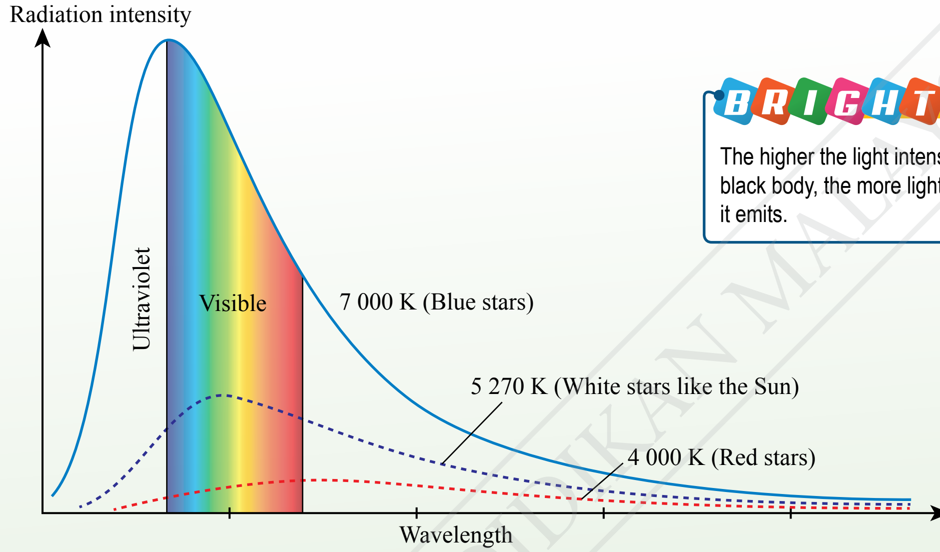
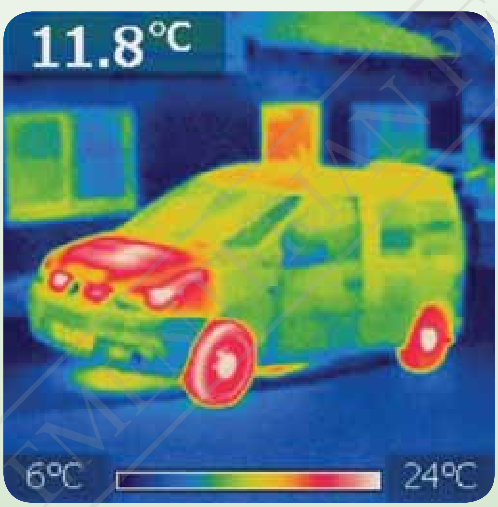


Figure 7.2 *Graph of radiation intensity against wavelength*

BRIGHT Info

The higher the light intensity of a black body, the more light energy it emits.



(a) Thermographic image of a car

SCAN ME

Video of infrared thermometer

https://bit.ly/2QjK78d

(b) Oven heating element

(c) Thermal radiation in light bulbs at different temperatures

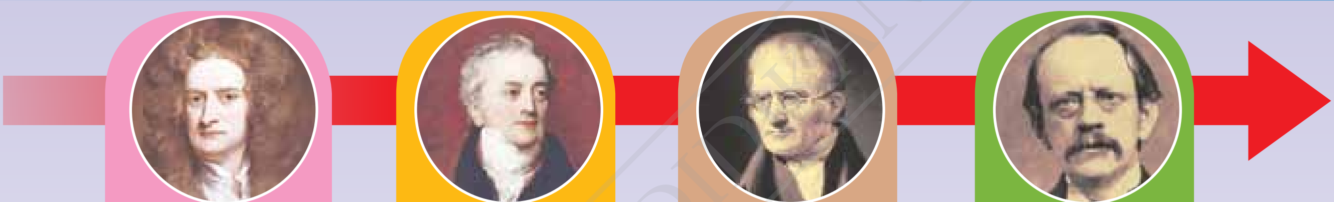
Photograph 7.1 *Examples of black bodies in daily life*

Ideas that Sparked the Quantum Physics Theory

Light is an electromagnetic wave that is produced from the vibration of an electric charge. In a hot object, electrons vibrate rapidly and randomly in any direction and produce light. As the object becomes hotter, the vibrations of the electrons become more energetic and more light will be emitted. The electrons in a hot object will vibrate in a continuous frequency range. According to classical theory, electrons vibrating at the same frequency should have the same energy content. The vibration frequency of the electrons also has no limits. Thus, the light energy produced by the vibration of electrons can reach unlimited high values.

However, experimental results involving black-body radiation are inconsistent with classical physics theory. Based on the graph of radiation intensity against wavelength for black-body radiation, the light intensity on the left side of the peak does not continue to increase with the increase of wave frequency as predicted by classical theory. This controversy in the concept of light energy has sparked the theory of quantum physics.

Classical Theory



Isaac Newton (1643 – 1727)	Thomas Young (1773 – 1829)	John Dalton (1766 – 1844)	J. J. Thomson (1856 – 1940)
The particle nature of light	**Double-slit experiment**	**Dalton Atomic Model**	**Discovery of Electrons**
• Described light as a single stream of particles or corpuscles in 1704. • Unsuccessful in explaining the phenomenon of light refraction due to failure in comparing the speed of light in glass and air.	• Conducted double-slit experiment on light in 1801 and showed that light is a wave. • Unable to explain the radiation spectrum produced by black bodies.	• Matter consists of basic particles that cannot be further divided called **atoms**. • Same elements have the same type of atoms. • Unable to explain the light spectrum produced by atoms.	• Discovered negatively charged subatomic particles called **electrons** in 1897. • Designed experiment to study the behaviour of electrons. • Unable to explain the line spectrum of light produced by atoms.

SCAN ME
Isaac Newton
https://bit.ly/3hpP4YX

SCAN ME
Thomas Young
https://bit.ly/34oRofj

SCAN ME
John Dalton
https://bit.ly/2CRvhTc

SCAN ME
J. J. Thomson
https://bit.ly/2YpGTo4

***Figure 7.3** The development of quantum theory from classical theory*

Activity 7.1

ISS ICS

Aim: To gather information on the development of quantum theory

Instructions:

1. Carry out a Gallery Walk activity.
2. Obtain information from various reading materials and websites about the findings of the following physicists which contribute to the development of quantum theory.

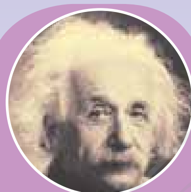
Isaac Newton	John Dalton	Max Planck	Niels Bohr
Thomas Young	J. J. Thomson	Albert Einstein	Louis de Broglie

3. Present your findings in the form of a mind map.

Quantum Theory

Max Planck
(1858 – 1947)

- Introduced the concept of **quantum** (discrete energy) in 1900
- The electromagnetic wave emitted by a black body is in discrete form known as quantum of energy.
- The energy in each quantum is directly proportional to the wave frequency.
- The intensity of the radiation is low for the high frequency waves.



Albert Einstein
(1879 – 1955)

- Introduced the **photon** concept in 1905.
- The photon energy is directly proportional to the light waves frequency.
- **Einstein's quantum theory of light** was successful in explaining the characteristics of the photoelectric effect that could not be explained by classical theory.

Niels Bohr
(1885 – 1962)

- Explained the production of line spectrum by hydrogen atoms.
- The electrons in an atom orbit around its nucleus on certain shells only.
- The transition of electrons from a higher energy level shell to a lower energy level shell emits photons.

Louis de Broglie
(1892 – 1987)

- Introduced the hypothesis on the wave nature of particles in 1924.
- Einstein and de Broglie postulated the idea of the **wave-particle duality** of light and all subatomic particles.

SCAN ME
Max Planck
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SCAN ME
Albert Einstein
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SCAN ME
Niels Bohr
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SCAN ME
Louis de Broglie
https://bit.ly/3aYrtw7

LS 7.1.1

Quantum of Energy

The electromagnetic spectrum may be a continuous spectrum or a line spectrum. Figures 7.4 and 7.5 show examples of a continuous spectrum and a line spectrum respectively.

SCAN ME
The line spectrum of several elements
https://bit.ly/3j6k4xC

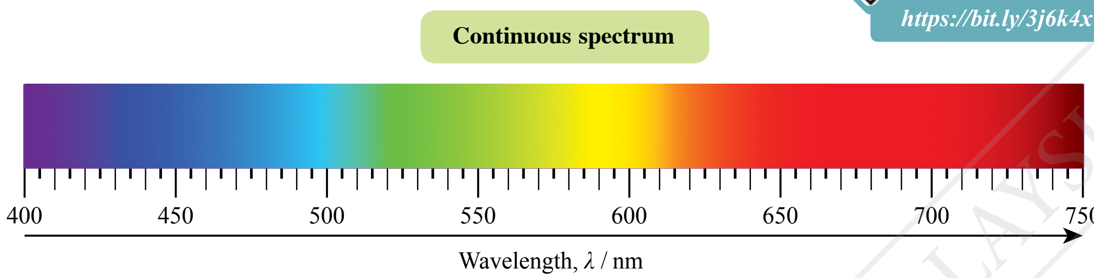


Figure 7.4 *Visible light spectrum*

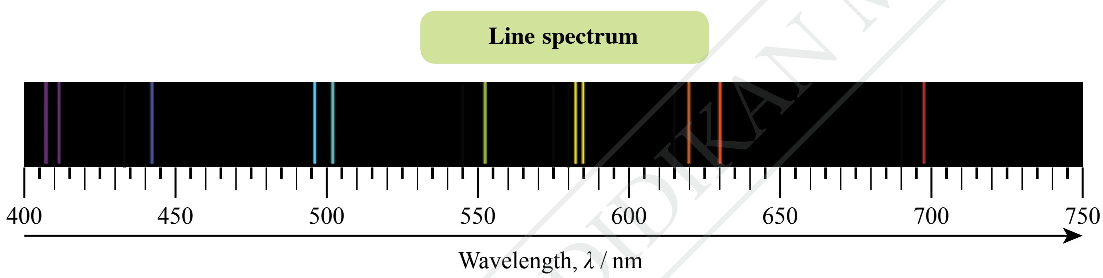


Figure 7.5 *Line spectrum of hot mercury vapour lamp*

The dispersion of white light by a prism produces a continuous spectrum consisting of seven visible colours. This spectrum has a wavelength range from 400 nm to 750 nm. The visible light spectrum is said to be continuous because there is no separation gap between each colour in the spectrum.

The line spectrum produced by an excited atom is a series of coloured lines with unique wavelengths and frequencies. Each element produces a spectrum with a series of its own distinctive lines. Therefore, the line spectrum can be used to identify the presence of an element. Table 7.1 shows the frequency and quantum of energy values of the line spectrum produced by a mercury vapour lamp.

Table 7.1 *Frequency and energy quantum values of a line spectrum from a mercury vapour lamp*

Line spectrum colour	Frequency, f / 10^{14} Hz	Energy quantum , E / 10^{-19} J
Violet	7.41	4.91
Blue	6.88	4.56
Green	5.49	3.65
Yellow-orange	5.19	3.44

Activity 7.2

ISS / ICS

Aim: To compare the concepts of continuous energy and discrete energy

Instructions:

1. Carry out this activity in groups.
2. Gather information related to the concepts of continuous energy and discrete energy on the following aspects:
   (a) the visible light spectrum
   (b) the line spectrum of mercury lamps and other lamps
   (c) differences between continuous energy and discrete energy
3. You can obtain information from websites or various reading sources.
4. Present your findings using a graphical map.

Quantum of energy is **discrete energy packet and not a continuous energy**. The energy depends on the frequency of the waves. According to Max Planck and Albert Einstein's quantum theory, light energy exists in the form of an energy packet known as a photon. Photons are light energies transferred in quantum of energy. The **photon** energy is directly proportional to the frequency of light waves. The higher the frequency of light waves, the higher the energy quantum of a photon.

$$E \propto f$$
$$E = hf$$

where E = photon energy
h = Planck's constant (6.63×10^{-34} J s)
f = frequency of light waves

Info GALLERY

Light is a type of electromagnetic wave. It also behaves as a particle. Other types of waves in the electromagnetic spectrum can also behave as particles.

Example 1

Compare the energy of a 400 nm and a 750 nm light photons.

LET'S ANSWER
https://bit.ly/34tx1NS

Solution

Step 1: Identify the problem	Step 2: Identify the information given	Step 3: Identify the formula to be used	Step 4: Solve the problem numerically

1. Energy of a 400 nm photon
   Energy of a 750 nm photon

2. Planck's constant, $h = 6.63 \times 10^{-34}$ J s
   Speed of light in vacuum, $c = 3.00 \times 10^{8}$ m s^{-1}
   Wavelength, $\lambda_1 = 400 \times 10^{-9}$ m
   Wavelength, $\lambda_2 = 750 \times 10^{-9}$ m

3. $c = \lambda f$, then $f = \dfrac{c}{\lambda}$
   $E = hf = \dfrac{hc}{\lambda}$

4. $E_1 = 6.63 \times 10^{-34}\left(\dfrac{3.00 \times 10^{8}}{400 \times 10^{-9}}\right)$
   $= 4.97 \times 10^{-19}$ J
   $E_2 = 6.63 \times 10^{-34}\left(\dfrac{3.00 \times 10^{8}}{750 \times 10^{-9}}\right)$
   $= 2.65 \times 10^{-19}$ J

The shorter the wavelength of light, the higher the photon energy.

LS 7.1.2 7.1.4

Wave-Particle Duality

Electromagnetic radiation such as light is said to have wave properties because it exhibits the phenomena of diffraction and interference. Objects like marbles are said to have particle properties because they possess momentum and kinetic energy and can collide with each other.

Activity 7.3

ISS ICS

Aim: To observe the wave properties of a particle and how the de Broglie wavelength changes with mass and particle velocity

Instructions:

1. Carry out this activity in pairs.
2. Scan the QR code to view the simulation of the wave properties of particles. Based on the simulation, discuss the following:
   (a) the wave nature of particles
   (b) the relationship between the de Broglie wavelength and the mass and velocity of the particle
3. Present your findings.

SCAN ME
Wavelength simulation
http://bit.ly/39xNYqu

In 1924, Louis de Broglie ('de Broy') (1892 – 1987), a quantum physicist, had put forward a hypothesis stating that all particles can exhibit wave characteristics. However, it is experimentally difficult to show the wave characteristics of particles with large masses. Louis de Broglie predicted that the wave characteristics can be exhibited by light particles, for example electrons. He stated that the relationship between the momentum of a particle, p and its wavelength, λ is as follows:

$$\lambda = \frac{h}{p}$$

where λ = wavelength
h = Planck's constant
p = momentum of particle

Value of Planck's constant is 6.63×10^{-34} J s.

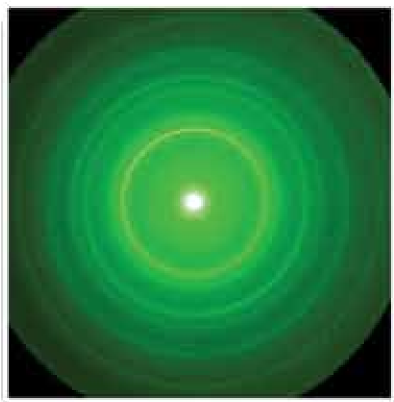
The greater the momentum of the particle, the shorter the wavelength. Since the value of the momentum of particle can be determined by $p = mv$, the following formula can also be obtained.

$$\lambda = \frac{h}{mv}$$

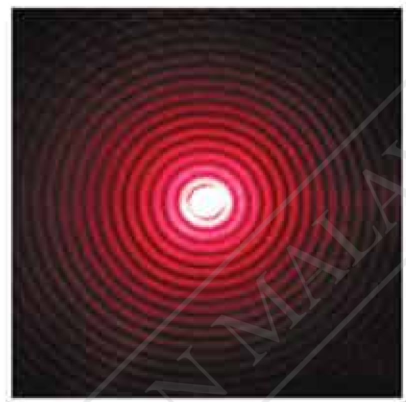
where m = mass of particle
v = velocity of particle

Since the value of h is very small, particles of large masses will have de Broglie wavelengths which are too short to be detected. Therefore, the wave characteristics cannot be observed.

In 1927, the presence of wave properties of electrons was confirmed through electron diffraction experiments. Photograph 7.2 shows the diffraction pattern of electrons through a thin layer of graphite. This pattern resembles the light diffraction pattern through an aperture as shown in Photograph 7.3. This confirmed de Broglie's hypothesis.

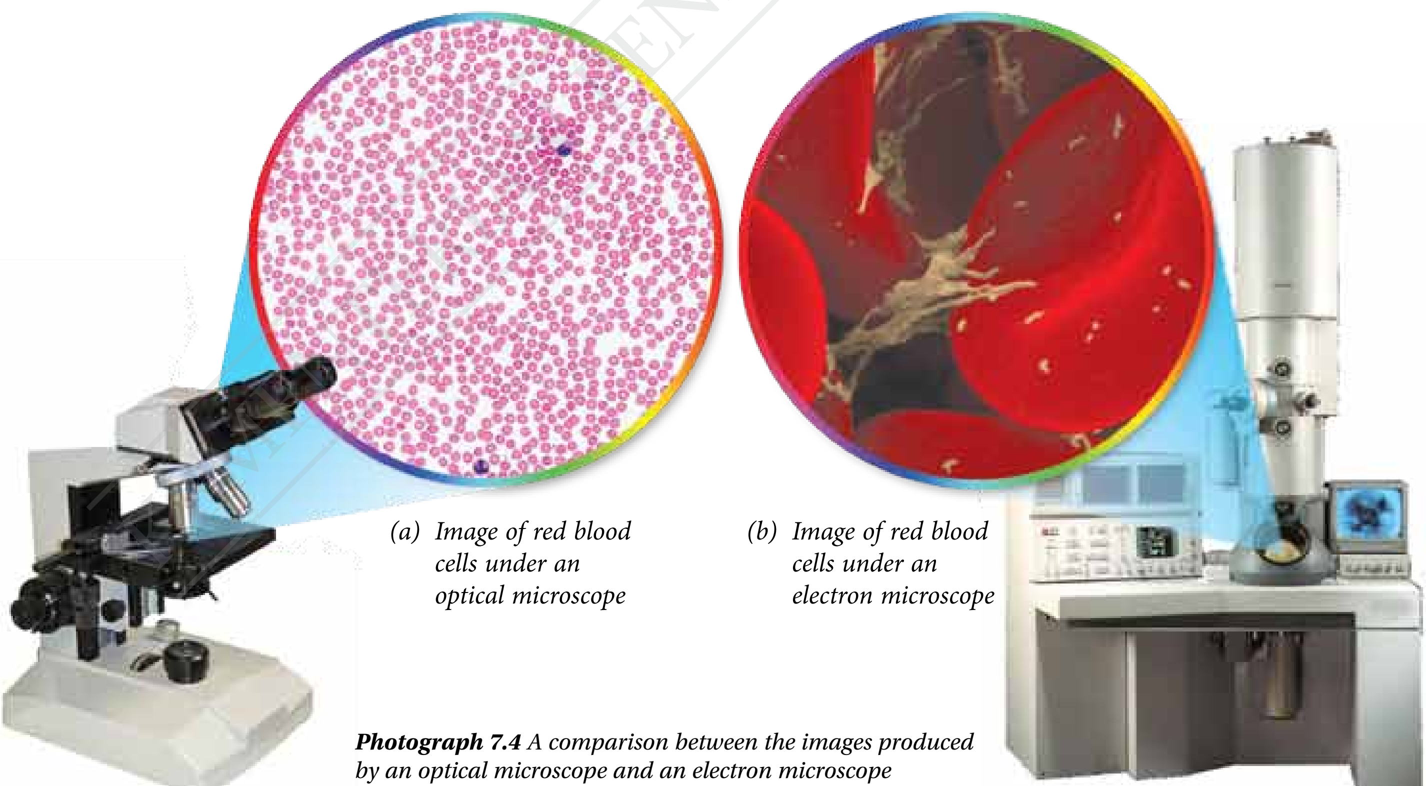


Photograph 7.2 *Diffraction pattern of electrons through a thin layer of graphite*



Photograph 7.3 *Diffraction pattern of red laser light through an aperture*

The de Broglie wavelength of an electron beam is approximately 1000 – 10 000 times shorter compared to the wavelength of light. This property is very important for higher magnification of electron microscope. A comparison between the images produced by an optical microscope and an electron microscope is shown in Photograph 7.4.



(a) Image of red blood cells under an optical microscope

(b) Image of red blood cells under an electron microscope

Photograph 7.4 *A comparison between the images produced by an optical microscope and an electron microscope*

Electrons are said to have wave-particle duality because they exhibit the properties of both particles and waves. Light also possesses both wave and particle properties. Therefore, light and electrons are said to have wave-particle duality. This duality is also found in all kinds of radiation in the electromagnetic wave spectrum as well as in subatomic particles like protons and neutrons.

Light energy, E is transmitted in energy packets known as photons

$$E = hf$$

where h = Planck's constant
f = frequency of light waves

For electromagnetic waves, the relationship between the wave speed, c with the wavelength, λ is $c = f\lambda$, then $f = \frac{c}{\lambda}$, and

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

Problem Solving for Photon Energy and Power

Energy for one photon, $E = hf$
Assuming that n photons are being emitted per second, then photons power, P which is the total energy transfer per second is

$$P = nhf = \frac{nhc}{\lambda}$$

Example 1

A 50 W lamp emits red light with a wavelength, $\lambda = 7.0 \times 10^{-7}$ m.
What is the number of photons emitted per second?

LET'S ANSWER
https://bit.ly/34HxegP

Solution

Step 1: Identify the problem

Step 2: Identify the information given

Step 3: Identify the formula to be used

Step 4: Solve the problem numerically

1. Number of photons emitted per second, n

2. Wavelength, $\lambda = 7.0 \times 10^{-7}$ m
Power, $P = 50$ W
Planck's constant, $h = 6.63 \times 10^{-34}$ J s
Speed of light in vacuum, $c = 3.00 \times 10^{8}$ m s^{-1}

3. $P = \frac{nhc}{\lambda}$
Then, $n = \frac{P\lambda}{hc}$

4. $n = \frac{50 \times 7.0 \times 10^{-7}}{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}$
$= 1.76 \times 10^{20}$ s^{-1}

Example 2

A red laser pen emits light with a wavelength of 670 nm. If the number of photons emitted is 3.37×10^{18} per second, what is the output power of the laser pen?

Solution

Wavelength, $\lambda = 670$ nm
$= 6.7 \times 10^{-7}$ m

Number of photons emitted per second, $n = 3.37 \times 10^{18}\ \text{s}^{-1}$

Planck's constant, $h = 6.63 \times 10^{-34}$ J s

Speed of light in vacuum, $c = 3.00 \times 10^{8}\ \text{m s}^{-1}$

Output power of the laser pointer, $P = \dfrac{nhc}{\lambda}$

$$= \frac{(3.37 \times 10^{18})(6.63 \times 10^{-34})(3.00 \times 10^{8})}{6.7 \times 10^{-7}}$$

$= 1.00$ W

Example 3

Assuming that 10% of the output power of a 100 W bulb is used to emit 2.92×10^{19} photons per second, what is the average wavelength of the light in nm?

Solution

Output power of photons emitted, $P = 10\% \times 100$ W
$= 10$ W

Number of photons emitted per second, $n = 2.92 \times 10^{19}\ \text{s}^{-1}$

Planck's constant, $h = 6.63 \times 10^{-34}$ J s

Speed of light in vacuum, $c = 3.00 \times 10^{8}\ \text{m s}^{-1}$

Average wavelength of light, $\lambda = \dfrac{nhc}{P}$

$$= \frac{(2.92 \times 10^{19})(6.63 \times 10^{-34})(3.00 \times 10^{8})}{10}$$

$= 5.81 \times 10^{-7}$ m
$= 581$ nm

Formative Practice 7.1

1. What is the frequency and energy of a photon with a wavelength of 10 nm?
2. How many photons are emitted per second by a 50 W green light lamp?
   [Frequency of green light, $f = 5.49 \times 10^{14}$ Hz]
3. Given that the mass of an electron is 9.11×10^{-31} kg:
   (a) what is the de Broglie wavelength of an electron beam with 50 eV kinetic energy?
   [1 eV = 1.60×10^{-19} J]
   (b) name a phenomenon that shows the wave properties of electrons.

7.2 Photoelectric Effect

When a metal surface is illuminated by a beam of light at a certain frequency, electrons can be emitted from the metal. This phenomenon is known as **photoelectric effect**.

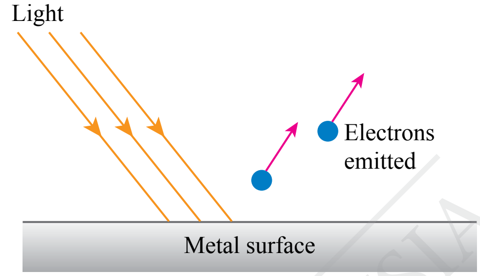


Figure 7.6 *Photoelectric effect*

Activity 7.4

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Aim: To study photoelectric effect

Instructions:

1. Carry out this activity in pairs.
2. Scan the QR code to watch a simulation on photoelectric effect.
3. Based on the simulation, study photoelectric effect.
4. Present your findings.

SCAN ME
Simulation of photoelectric effect
http://bit.ly/2SGY8PM

The characteristics of photoelectric effect can be studied by arranging a photocell in the circuit as shown in Figure 7.7.

SCAN ME
Demonstration video of photoelectric effect
https://bit.ly/2EsWSuu

1 When a light sensitive metal surface (cathode) is illuminated with a certain light beam, electrons will be emitted from the metal surface. These electrons are called photoelectrons.

2 The emitted photoelectrons are attracted to the anode which has positive potential.

3 The movement of the photoelectrons from the cathode to the anode produces a current inside the circuit. The milliammeter shows the value of the current.

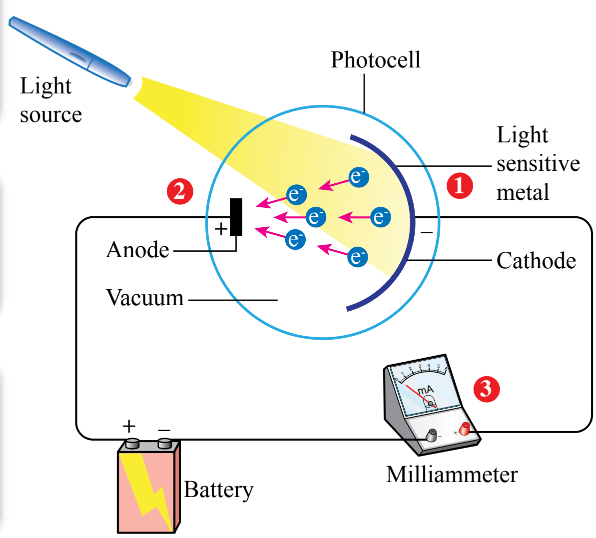

Figure 7.7 *Apparatus to show photoelectric effect*

LS 7.2.1

Formulae such as $E = hf$ and $\lambda = \dfrac{h}{p}$, involve Planck's constant, h. How can the value of this constant, h be determined in the laboratory?

Activity 7.5

Aim: To determine the value of Planck's constant using the Planck's constant kit

Apparatus: Planck's constant kit (9 V battery, 1 kΩ potentiometer, LEDs of different colours, milliammeter and voltmeter)

Instructions:

1. Using the red LED, connect the Planck's constant kit as shown in Figure 7.8.
2. Scan the QR code to print Table 7.2.
3. Adjust the knob on the potentiometer to obtain the voltage, V = 0.2 V. Record the milliammeter reading in Table 7.2.
4. Repeat step 3 for V = 0.4 V, 0.6 V, 0.8 V, ..., 3.0 V.
5. Draw a graph of current against voltage. Based on the graph intercept value on the voltage axis, determine the activation voltage, V_a of the red LED.
6. Repeat steps 3 to 5 using orange, green and blue LEDs.

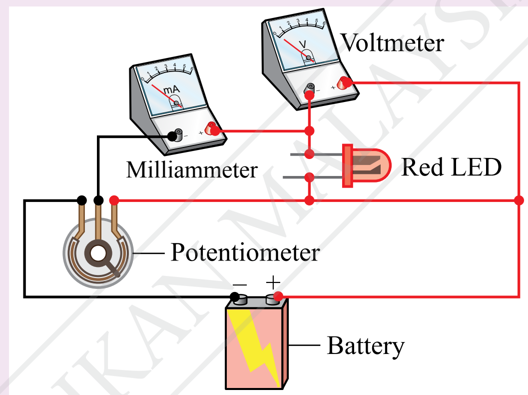

Figure 7.8

SCAN ME
Worksheet (Table 7.2)
https://bit.ly/2RpGiyZ

SCAN ME
Video to determine the value of Planck's constant
https://bit.ly/2QoFVUC

Results:

Table 7.2

LED colour ______________

Voltage, V / V	Current, I / mA
0.20	
0.40	
0.60	

Data analysis:

1. Based on the value of the activation voltage that is obtained from the graph of current, I against voltage, V for each LED colour, complete Table 7.3.

Table 7.3

LED Colour	Wavelength, λ / nm	Activation voltage, V_a / V	$\dfrac{1}{\lambda}$ / m^{-1}
Red	623		
Orange	586		
Green	567		
Blue	467		

2. Based on Table 7.3, plot the graph of V_a against $\frac{1}{\lambda}$.
3. Based on the graph plotted, determine the gradient, m of the graph and calculate Planck's constant, h. Given

$h = \frac{me}{c}$, where e = charge of an electron (1.60×10^{-19} C)
c = speed of light in vacuum (3.00×10^{8} m s^{-1})

SCAN ME
Determine the value of Planck's constant through the gradient of the graph

https://bit.ly/32pUDAv

Discussion:
What is the relationship between the activation voltage and the LED light wavelength?

The activation voltage, V_a can be obtained through V-intercept from the graph of I against V as shown in Figure 7.9. The activation voltage, V_a has a linear relationship with $\frac{1}{\lambda}$ as shown in Figure 7.10. Gradient of a graph of V_a against $\frac{1}{\lambda}$, m is equal to the value of $\frac{hc}{e}$. Therefore, the value of Planck's constant can be determined as $\frac{me}{c}$.

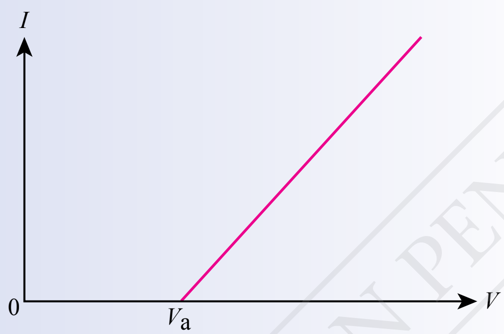

Figure 7.9 *Graph of I against V*

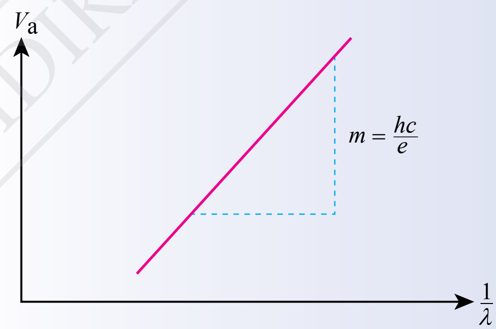

Figure 7.10 *Graph of V_a against $\frac{1}{\lambda}$*

The Characteristics of the Photoelectric Effect

Activity 7.6

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Aim: To gather information on the four characteristics of the photoelectric effect

Instructions:
1. Carry out a Gallery Walk activity.
2. Obtain information from various reading materials and websites on the following four characteristics of the photoelectric effect:
   (a) the effect of frequency on the photoelectric effect
   (b) the existence of a threshold frequency
   (c) the effect of the intensity of light on the kinetic energy of photoelectron
   (d) the instantaneous emission of photoelectrons when light shines on it
3. Present your findings.

Photoelectric effect occurs when light strikes the surface of a metal. The electrons in the metal absorb energy from the light and escape from the metal surface. According to classical theory, light in wave form is a spectrum with continuous energy and photoelectric effect should be able to occur at any light wave frequency. Bright light which has high energy should be able to emit electrons quickly. Dim light has low energy so the electrons need a longer time to absorb enough energy to escape from the metal surface.

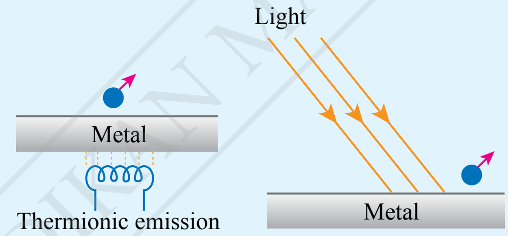
However, the results of the photoelectric effect experiments show that the emission of photoelectrons only apply to light waves with frequencies that exceed a certain value without being affected by the intensity of the light. Photoelectrons are also emitted instantaneously at those light frequencies even at low light intensities.

1. The higher the frequency of the photon of light, the higher the kinetic energy of the photoelectrons emitted from the metal surface.

2. The minimum frequency of light needed for a metal to emit electrons is known as the threshold frequency, f_0 for that metal.

3. The kinetic energy of photoelectrons does not depend on the intensity of light. An increase in the light intensity does not produce photoelectrons with a higher kinetic energy.

4. Photoelectrons are emitted instantaneously when a metal surface is illuminated by light.



- The emission of electrons from a metal surface by thermionic emission may take some time.
- The emission of electrons from a metal surface by photoelectric effect is instantaneous.

Figure 7.11 *The characteristics of photoelectric effect*

The threshold frequency, f_0 is the minimum frequency required to produce photoelectric effect on a metal.

Formative Practice 7.2

1. What is meant by photoelectric effect?
2. Will a bright light emit more photoelectrons from a metal surface compared to a dim light of the same frequency?
3. State four characteristics of photoelectric effect that are obtained experimentally.
4. Why are photoelectrons emitted instantaneously from a metal surface when it is illuminated by a light of certain frequency?
5. Does an increase in the light intensity increase the kinetic energy of the photoelectrons? Why?

LS 7.2.2

7.3 Einstein's Photoelectric Theory

In 1905, Albert Einstein introduced a photoelectric theory that successfully explained all the characteristics of photoelectric effect in related experiments. He was awarded the Nobel Prize in 1921 for this achievement. This theory is named **Einstein's Photoelectric Theory**.

Einstein applied Max Planck's idea of energy quantum. He suggested that energy is carried by light particles called photons. The energy of each photon is directly proportional to the frequency of light, f and can be determined by the following equation.

$$E = hf$$

where h = Planck's constant (6.63×10^{-34} J s)

Each quantum of light is a discrete packet of energy. There are many energy packets in a beam of light that shines on the metal surface. When a photon arrives at a metal surface, the photon energy will be fully absorbed by an electron in the metal. This energy is used to release the electron from the metal and the extra energy will become the kinetic energy of the photoelectron. Usually, the electrons on a metal surface will acquire maximum kinetic energy compared to the electrons inside the metal.

For the electrons on the metal surface,

photon energy = minimum energy required to release a photoelectron + maximum kinetic energy of a photoelectron

$$E = W + K_{max}$$

$$hf = W + \frac{1}{2}mv^2_{max}$$

$$\frac{1}{2}mv^2_{max} = hf - W$$

Einstein's Photoelectric Equation is in accordance with the Principle of Conservation of Energy.

At the threshold frequency, f_0, photoelectrons are emitted without any kinetic energy, $\frac{1}{2}mv^2_{max} = 0$

Then, $0 = hf_0 - W$

$W = hf_0$

Substitute $W = hf_0$ into $\frac{1}{2}mv^2_{max} = hf - W$

$$\frac{1}{2}mv^2_{max} = hf - hf_0$$

$$\frac{1}{2}mv^2_{max} = h(f - f_0)$$

LS 7.3.1

Work Function and Threshold Frequency for Photoelectric Effect

The minimum energy required for a photoelectron to be emitted from a metal surface is known as **work function**. **The minimum frequency for a light photon to produce photoelectric effect** is called **threshold frequency**.

The relationship between the maximum kinetic energy of photoelectrons, K_{max} and the light frequency, f is shown by the graph in Figure 7.12. The graph is a straight line with a positive gradient and not passing through the origin. The threshold frequency, f_0 is the value of the intercept on the frequency axis.

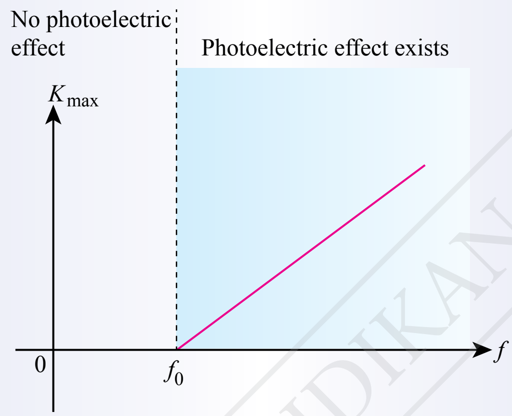


***Figure 7.12** Graph of K_{max} against f*

The relationship between work function and threshold frequency of a metal can be determined by the relationship $W = hf_0$. Photoelectrons will acquire kinetic energy when light frequency exceeds threshold frequency. The higher the threshold frequency of a metal, the higher the work function. This means the minimum energy required for photoelectric effect to occur is higher. Different metals have different threshold frequencies as shown in Figure 7.13.

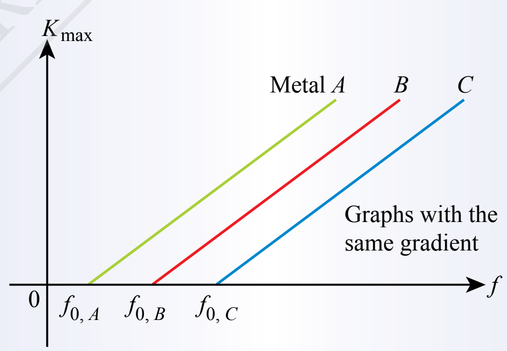


***Figure 7.13** Graphs of K_{max} against f for different types of metals*

Activity 7.7

ISS / ICS

Aim: To observe threshold frequencies of different metals

Instructions:

1. Carry out this activity in pairs.
2. Scan the QR code to observe computer simulations using violet, blue, green, yellow, orange and red lights to understand that different metals have different threshold frequencies.
3. Gather information on the types of metal and the threshold frequencies for each colour of light observed.
4. Present your findings.

SCAN ME
Simulations of threshold frequencies
http://bit.ly/2SGY8PM

Activity 7.8

Aim: To determine work function of metals using a formula

Instructions:

1. Carry out this activity in pairs.
2. Examine the following equations:

Using Einstein's equation, $K_{max} = hf - W$

If $K_{max} = 0$ and $f = f_0$

$hf_0 - W = 0$

then, $W = hf_0$

3. Determine work function for each type of metal and complete Table 7.4.

Table 7.4

Type of metal	Threshold frequency, f_0 / 10^{14} Hz	Work function, $W = hf_0$ / J
Ta	1.03	
Ti	1.05	
Mo	1.11	
Au	1.23	
Pd	1.24	
Ir	1.27	
Pt	1.36	