

# 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



## 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.

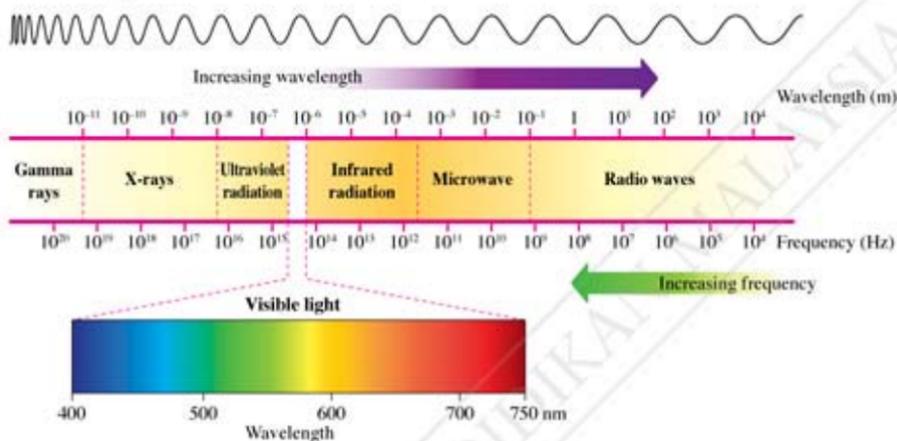


Figure 7.1 Electromagnetic spectrum

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?

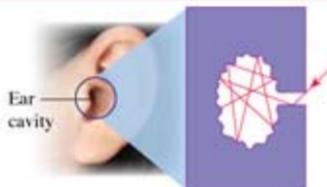
A **black body** is an idealised body that is able to absorb all electromagnetic radiation that falls on it. A black body can also emit thermal radiation depending on its temperature. The radiation emitted forms a continuous spectrum and is unaffected by the nature of the black body surface. Thus, an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

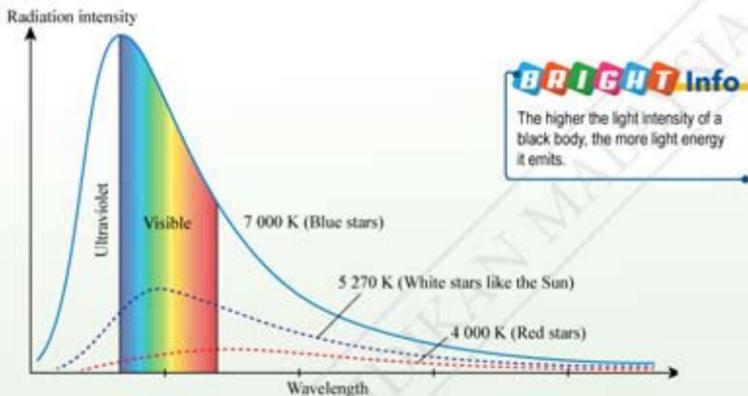


Figure 7.2 Graph of radiation intensity against wavelength

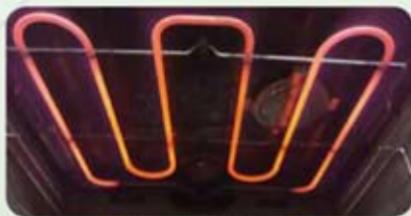


(a) Thermographic image of a car

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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)

#### The particle nature of light

- 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.



Thomas Young  
(1773 – 1829)

#### Double-slit experiment

- 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.



John Dalton  
(1766 – 1844)

#### Dalton Atomic Model

- 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.



J. J. Thomson  
(1856 – 1940)

#### Discovery of Electrons

- 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.

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Isaac Newton

<https://bit.ly/3hpP4YX>

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Thomas Young

<https://bit.ly/34oRuff>

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John Dalton

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J. J. Thomson

<https://bit.ly/2YpGT04>

Figure 7.3 The development of quantum theory from classical theory

## Activity 7.1

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**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

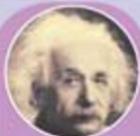
3. Present your findings in the form of a mind map.

## 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.

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Max Planck


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Albert Einstein


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Niels Bohr


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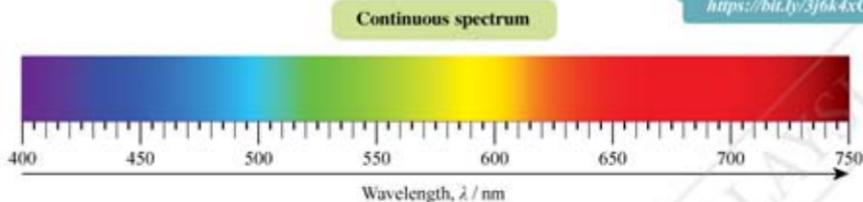
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Louis de Broglie

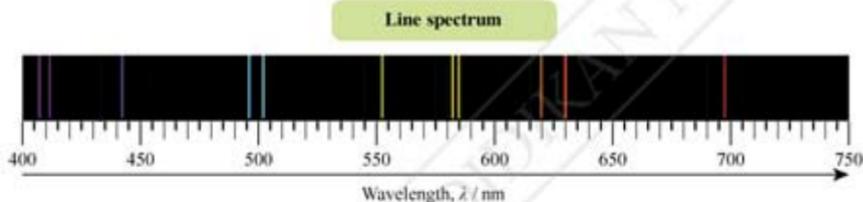

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## Quantum of Energy

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.



**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

**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 ( $6.63 \times 10^{-34}$  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.

## 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<sup>-1</sup>  
 Wavelength,  $\lambda_1 = 400 \times 10^{-9}$  m  
 Wavelength,  $\lambda_2 = 750 \times 10^{-9}$  m

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

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

## LET'S ANSWER



<https://bit.ly/34tc1NS>

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

## 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

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**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,  $\lambda$  is as follows:

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

where  $\lambda$  = wavelength  
 $h$  = Planck's constant  
 $p$  = momentum of particle

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

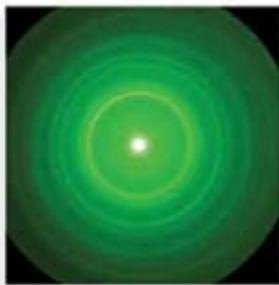
The greater the momentum of the particle, the shorter the wavelength. Since the value of the momentum of particle can be determined by  $p = mv$ , the following formula can also be obtained.

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

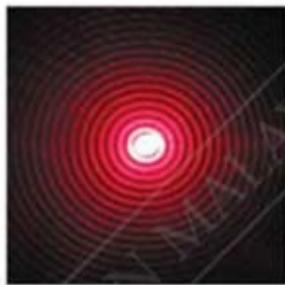
where  $m$  = mass of particle  
 $v$  = velocity of particle

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.

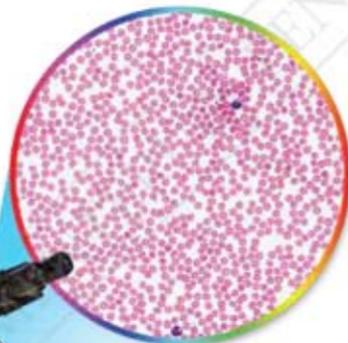


**Photograph 7.2** Diffraction pattern of electrons through a thin layer of graphite

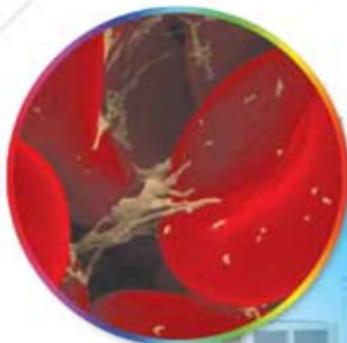


**Photograph 7.3** Diffraction pattern of red laser light through an aperture

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,  $\lambda$  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?

#### 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<sup>-1</sup>

3 
$$P = \frac{nhc}{\lambda}$$

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

4 
$$n = \frac{50 \times 7.0 \times 10^{-7}}{6.63 \times 10^{-34} \times 3.00 \times 10^8}$$
  

$$= 1.76 \times 10^{20} \text{ s}^{-1}$$

#### LET'S ANSWER



<https://bit.ly/34HxegP>

**Example 2**

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

**Solution**

$$\begin{aligned}\text{Wavelength, } \lambda &= 670 \text{ nm} \\ &= 6.7 \times 10^{-7} \text{ m}\end{aligned}$$

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

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

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

$$\begin{aligned}\text{Output power of the laser pointer, } P &= \frac{nhc}{\lambda} \\ &= \frac{(3.37 \times 10^{18})(6.63 \times 10^{-34})(3.00 \times 10^8)}{6.7 \times 10^{-7}} \\ &= 1.00 \text{ W}\end{aligned}$$

**Example 3**

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

**Solution**

$$\begin{aligned}\text{Output power of photons emitted, } P &= 10\% \times 100 \text{ W} \\ &= 10 \text{ W}\end{aligned}$$

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

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

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

$$\begin{aligned}\text{Average wavelength of light, } \lambda &= \frac{nhc}{P} \\ &= \frac{(2.92 \times 10^{19})(6.63 \times 10^{-34})(3.00 \times 10^8)}{10} \\ &= 5.81 \times 10^{-7} \text{ m} \\ &= 581 \text{ nm}\end{aligned}$$

**Formative Practice 7.1**

- What is the frequency and energy of a photon with a wavelength of 10 nm?
- 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]
- Given that the mass of an electron is  $9.11 \times 10^{-31}$  kg:
  - what is the de Broglie wavelength of an electron beam with 50 eV kinetic energy?   
[1 eV =  $1.60 \times 10^{-19}$  J]
  - 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**.

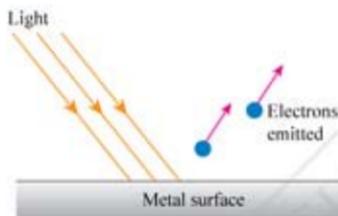


Figure 7.6 Photoelectric effect

### 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/2EsWSau>

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.

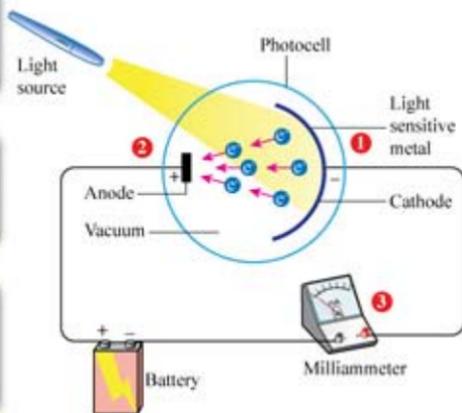


Figure 7.7 Apparatus to show photoelectric effect

Formulae such as  $E = hf$  and  $\lambda = \frac{h}{p}$ , 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 k $\Omega$  potentiometer, LEDs of different colours, milliammeter and voltmeter)

### Instructions:

- Using the red LED, connect the Planck's constant kit as shown in Figure 7.8.
- Scan the QR code to print Table 7.2.
- Adjust the knob on the potentiometer to obtain the voltage,  $V = 0.2$  V. Record the milliammeter reading in Table 7.2.
- Repeat step 3 for  $V = 0.4$  V,  $0.6$  V,  $0.8$  V, ...,  $3.0$  V.
- 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.
- Repeat steps 3 to 5 using orange, green and blue LEDs.

### Results:

Table 7.2

LED colour	
Voltage, $V/V$	Current, $I/mA$
0.20	
0.40	
0.60	

### Data analysis:

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

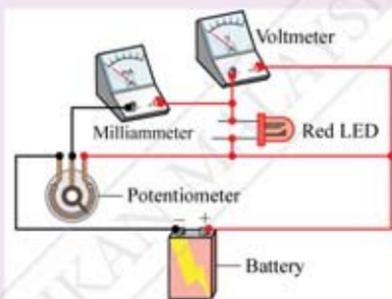


Figure 7.8



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Worksheet  
(Table 7.2)

<https://bit.ly/2RpGiyZ>



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Video to determine  
the value of  
Planck's constant

<https://bit.ly/2QoFVUC>

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

$$h = \frac{me}{c}, \text{ where } e = \text{charge of an electron } (1.60 \times 10^{-19} \text{ C})$$

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



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:**

- Carry out a Gallery Walk activity.
- Obtain information from various reading materials and websites on the following four characteristics of the photoelectric effect:
  - the effect of frequency on the photoelectric effect
  - the existence of a threshold frequency
  - the effect of the intensity of light on the kinetic energy of photoelectron
  - the instantaneous emission of photoelectrons when light shines on it
- 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.

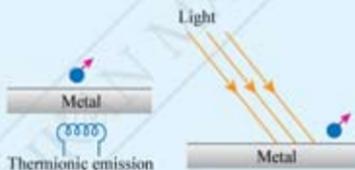
However, the results of the photoelectric effect experiments show that the emission of photoelectrons only apply to light waves with frequencies that exceed a certain value without being affected by the intensity of the light. Photoelectrons are also emitted instantaneously at those light frequencies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

## 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 ( $6.63 \times 10^{-34}$  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,

$$\text{photon energy} = \begin{array}{l} \text{minimum energy} \\ \text{required to release} \\ \text{a photoelectron} \end{array} + \begin{array}{l} \text{maximum} \\ \text{kinetic energy of} \\ \text{a photoelectron} \end{array}$$

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

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

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

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,  $\frac{1}{2}mv_{\max}^2 = 0$

$$\text{Then, } 0 = hf_0 - W$$

$$W = hf_0$$

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

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

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

## 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.

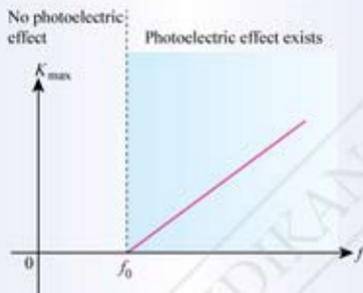


Figure 7.12 Graph of  $K_{\max}$  against  $f$

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.

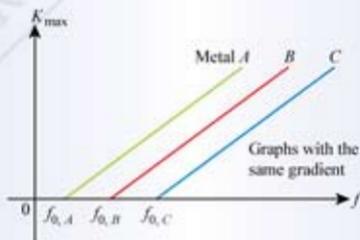


Figure 7.13 Graphs of  $K_{\max}$  against  $f$  for different types of metals

## Activity 7.7

**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, $W = hf_0 / \text{J}$
Ta	1.03	
Ti	1.05	
Mo	1.11	
Au	1.23	
Pd	1.24	
Ir	1.27	
Pt	1.36	

## Problem Solving Using Einstein's Photoelectric Equation

### Example 1

A blue light with a frequency of  $6.67 \times 10^{14}$  Hz is shone on a clean caesium metal surface. What is the maximum kinetic energy of photoelectrons emitted?

[Work function of caesium =  $3.43 \times 10^{-19}$  J, Planck's constant =  $6.63 \times 10^{-34}$  J s]

LET'S ANSWER



<https://bit.ly/2YwWUsj>

### Solution

#### Step 1:

Identify the problem

1 Maximum kinetic energy of the photoelectron,  $K_{\max}$

#### Step 2:

Identify the information given

2 Frequency,  $f = 6.67 \times 10^{14}$  Hz  
Work function,  $W = 3.43 \times 10^{-19}$  J  
Planck's constant,  $h = 6.63 \times 10^{-34}$  J s

#### Step 3:

Identify the formula to be used

$$3 \quad hf = W + K_{\max}$$

#### Step 4:

Solve the problem numerically

$$4 \quad (6.63 \times 10^{-34})(6.67 \times 10^{14}) = 3.43 \times 10^{-19} + K_{\max}$$

$$K_{\max} = 4.42 \times 10^{-19} - 3.43 \times 10^{-19}$$

$$= 9.92 \times 10^{-20} \text{ J}$$

### Example 2

Figure 7.14 shows the change in kinetic energy of photoelectrons released from lithium for different light frequencies. Determine the threshold frequency from the graph and calculate the work function of lithium.

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

### Solution

Threshold frequency,  $f_0 = 5.6 \times 10^{14}$  Hz

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

$$\begin{aligned} \text{Work function, } W &= hf_0 \\ &= (6.63 \times 10^{-34})(5.6 \times 10^{14}) \\ &= 3.71 \times 10^{-19} \text{ J} \end{aligned}$$

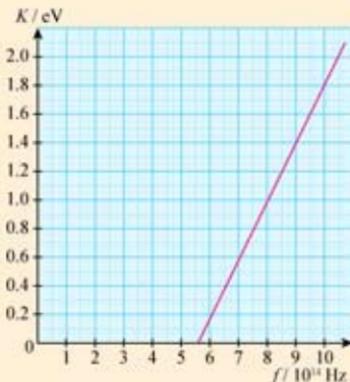


Figure 7.14

### Example 3

What is the maximum velocity of the photoelectron emitted when a monochromatic light ( $\lambda = 550 \text{ nm}$ ) is shone on a metal which has a work function of  $2.00 \text{ eV}$ ?  
 [Given  $hc = 1.243 \times 10^3 \text{ eV nm}$ ,  $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$ , mass of electron,  $m = 9.11 \times 10^{-31} \text{ kg}$ ]

### Solution

Wavelength,  $\lambda = 550 \text{ nm}$

$hc = 1.243 \times 10^3 \text{ eV nm}$

$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$

Mass of electron,  $m = 9.11 \times 10^{-31} \text{ kg}$

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

$$= \frac{1.243 \times 10^3 \text{ eV nm}}{550 \text{ nm}}$$

$$= 2.26 \text{ eV}$$

$$\text{Then } \frac{1}{2}mv_{\text{max}}^2 = 2.26 - 2.00$$

$$= 0.26 \text{ eV}$$

$$\frac{1}{2}mv_{\text{max}}^2 = 0.26 \times 1.60 \times 10^{-19} \text{ J}$$

$$= 4.16 \times 10^{-20} \text{ J}$$

$$v_{\text{max}} = \sqrt{\frac{2 \times 4.16 \times 10^{-20}}{9.11 \times 10^{-31}}}$$

$$= 3.02 \times 10^5 \text{ m s}^{-1}$$

### Example 4

When a photocell is shone on with a red light ( $\lambda_1 = 750 \text{ nm}$ ) and then with a blue light ( $\lambda_2 = 460 \text{ nm}$ ), the maximum kinetic energy of the photoelectron emitted by the blue light is two times that of the red light.

- (a) What is the work function of the photoelectric material in the photocell?  
 (b) What is the threshold wavelength of the photoelectric material?

### Solution

Wavelength of the red light,  $\lambda_1 = 750 \times 10^{-9} \text{ m}$

Wavelength of the blue light,  $\lambda_2 = 460 \times 10^{-9} \text{ m}$

Maximum kinetic energy of the photoelectron of the red light,  $K_1$

Maximum kinetic energy of the photoelectron of the blue light,  $K_2 = 2K_1$

Work function =  $W$

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

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

$$(a) \quad hf = W + K$$

$$\frac{hc}{\lambda} = W + K$$

$$6.63 \times 10^{-34} \times \left( \frac{3.00 \times 10^8}{750 \times 10^{-9}} \right) = W + K_1$$

$$2.65 \times 10^{-19} = W + K_1 \text{ ----- (1)}$$

$$6.63 \times 10^{-34} \times \left( \frac{3.00 \times 10^8}{460 \times 10^{-9}} \right) = W + K_2$$

$$4.32 \times 10^{-19} = W + 2K_1 \text{ ----- (2)}$$

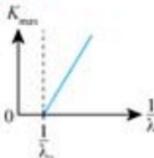
$$(1) \times 2 - (2):$$

$$2.65 \times 10^{-19} \times 2 - 4.32 \times 10^{-19} = (2W - W) + (2K_1 - 2K_1)$$

$$W = 9.80 \times 10^{-20} \text{ J}$$

### Info GALLERY

The maximum wavelength of light needed for a metal to emit electrons is known as threshold wavelength,  $\lambda_0$  for the metal.



$$(b) \quad \frac{hc}{\lambda_0} = W,$$

$$\lambda_0 = 6.63 \times 10^{-34} \times \left( \frac{3.00 \times 10^8}{9.80 \times 10^{-20}} \right)$$

$$= 2.03 \times 10^{-6} \text{ m}$$

## Generating Photoelectric Current in a Photocell Circuit

Figure 7.15 shows a photocell circuit consisting of a glass vacuum tube. The semi-cylindrical cathode is coated with a light-sensitive metal and connected to the negative potential. The anode is a metal rod fixed at the axis of the semi-cylindrical cathode and connected to the positive potential. When the photocell is illuminated by light, the production of photoelectric current is produced in the circuit. Table 7.5 are two examples of common photocells.

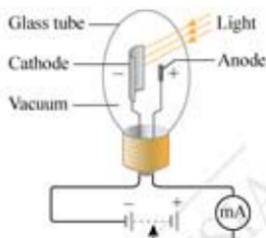


Figure 7.15 A photocell circuit

Table 7.5 Production of photoelectric current by photocells coated with caesium and lithium

Caesium	Lithium
Work function of caesium, $W = 2.14 \text{ eV}$	Work function of lithium, $W = 2.50 \text{ eV}$
Threshold frequency, $f_0 = 5.16 \times 10^{14} \text{ Hz}$	Threshold frequency, $f_0 = 6.03 \times 10^{14} \text{ Hz}$
Maximum wavelength to produce photoelectric current, $\lambda = 579 \text{ nm}$	Maximum wavelength to produce photoelectric current, $\lambda = 496 \text{ nm}$

On the whole, the higher the work function, the shorter the maximum wavelength required to produce photoelectric current. As the light intensity increases, the photoelectric current in the photocell circuit also increases.

### Activity 7.9

ISS / ICS

**Aim:** To observe how photoelectric current is produced in a photocells coated with caesium through computer animations

#### Instructions:

1. Carry out this activity in pairs.
2. Scan the QR code to view a simulation related to the production of photoelectric current in photocells coated with caesium.
3. Based on the simulation, explain how the photoelectric current is produced in a photocell coated with caesium.
4. Present your findings.



SCAN ME

Animation video on the production of photoelectric current

<https://bit.ly/3hrJJRr>

## Photoelectric Effect Applications

Figure 7.16 shows some examples of applications of photoelectric effect.



LED lamps along the road which are powered by solar cells are energy efficient and environmentally friendly. In daylight, the photoelectric effect of solar cells enables electrical energy to be stored in the battery. At night, the LED lamps will light up with the power from the battery.



The Noor Complex Solar Power Plant located in the Sahara Desert is the world's largest concentrated solar power plant. This station is expected to be completed in 2020 and is capable of producing 580 MW capacity for use by 1 million residents.

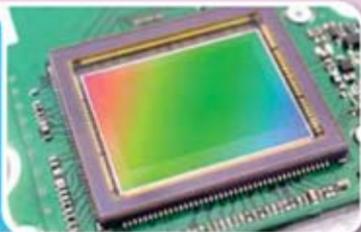


Light detectors at the automatic doors use infrared beam and photocells as switches. When the light path is disturbed, photoelectric current in the photocell circuit will be disconnected and the door will remain open.

Applications of Photoelectric Effect

Figure 7.16 Examples of applications of photoelectric effect

The image sensor is a main component in high-resolution cameras. This component is used to convert light into electrical signals which can be processed to form digital images.



The operation of the ISS (International Space Station) depends on the source of electrical energy generated from solar panels. The ISS has 16 wings of solar panels and each wing which measures  $35 \text{ m} \times 12 \text{ m}$  has 33 thousand solar cells. These panels are capable of generating 84 – 120 kW of electricity.



### Activity 7.10

ISS ICS

**Aim:** To gather information on the applications of photoelectric effect

**Instructions:**

1. Carry out a Round Table activity.
2. You can obtain information from reading materials or website about other applications of photoelectric effect.
3. Present your findings in a mind map.

### Formative Practice 7.3

1. (a) State Einstein's Photoelectric Equation.  
(b) State the meaning of:
  - (i) work function
  - (ii) threshold frequency
  - (iii) the relationship between work function and threshold frequency
2. (a) Sketch a graph to show the relationship between the maximum kinetic energy of photoelectrons and the frequency of light shone on a metal.  
(b) What are the physical quantities represented by the gradient and the intercepts of the graph sketched in 2(a)?
3. When a metal with a work function of  $4.32 \times 10^{-19} \text{ J}$  is shone on by a violet light ( $\lambda = 4 \times 10^{-7} \text{ m}$ ), what is the maximum kinetic energy of an emitted photoelectron? [Planck's constant,  $h = 6.63 \times 10^{-34} \text{ J s}$ , speed of light in vacuum,  $c = 3.00 \times 10^8 \text{ m s}^{-1}$ ]

Quantum Physics

Quantum Theory of Light

Explanation of black body spectrum

Max Planck

Discrete energy packet,  $E = hf$

waves with particle properties

de Broglie's hypothesis,  $\lambda = \frac{h}{p}$

particles with wave properties

Electron microscope

Photoelectric Effect

- The higher the light photon frequency, the higher the kinetic energy of the emitted photoelectrons.
- The minimum frequency to emit a photoelectron is the threshold frequency,  $f_0$ .
- The kinetic energy of photoelectrons is independent of the intensity of the light
- The emission of photoelectrons is instantaneous

• Photon energy,  $E = \frac{hc}{\lambda}$

• Power,  $P = nhf$

Einstein's Photoelectric Theory

explained by

- Einstein's Photoelectric Equation,  $hf = W + \frac{1}{2}mv_{max}^2$
- Work function,  $W = hf_0 = \frac{hc}{\lambda_0}$

Photoelectric current production

applications

- Solar cells
- Light detector of automatic door
- Image sensor
- ISS solar panel

## Self-Reflection

1. New things I have learnt in the chapter on 'Quantum Physics' are \_\_\_\_\_.
2. The most interesting thing I have learnt in this chapter is \_\_\_\_\_.
3. The things I still do not fully understand are \_\_\_\_\_.
4. My performance in this chapter.  
 Poor 😞 1 2 3 4 5 😊 Very good
5. I need to \_\_\_\_\_ to improve my performance in this chapter.


**SCAN ME**

 Download and print  
Self-Reflection

<https://bit.ly/2QiuNZA>

## Summative Practice


<https://bit.ly/3ht8T1t>

Values that can be used in solution:

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

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

 Mass of electron,  $m_e = 9.11 \times 10^{-31} \text{ kg}$ 
 $1.00 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$ 

1. State the meaning of the following terms:
  - (a) black body
  - (b) quantum of energy
2. The minimum energy required for the photoelectron to escape from the sodium metal surface is 2.28 eV.
  - (a) Will sodium show photoelectric effect for a red light with a wavelength of 680 nm shone on it?
  - (b) What is the threshold wavelength of sodium? 🍌

3. Wavelength of the yellow line of the sodium spectrum is 590 nm. How much kinetic energy does one electron have when its de Broglie wavelength is equal to the yellow line of the sodium spectrum? 🌸
4. A laser light beam with a wavelength of 555 nm and a power of 5.00 mW is aimed at an object without any light reflected. Calculate: 🌸
  - (a) the momentum of a photon in the laser beam
  - (b) the number of photons per second in the laser light beam hitting the object
5. The de Broglie wavelength of an electron is 1.00 nm.
  - (a) State Louis de Broglie's hypothesis of the wave properties of electrons.
  - (b) Calculate the momentum of the electron. 🌸
  - (c) Calculate the velocity of the electron. 🌸
  - (d) Calculate the kinetic energy of the electron. 🌸
6. (a) Why is a large cavity with a small hole able to act as a black body?  
 (b) The temperature of a black body is 4 500 K and it looks orange-yellow. Describe the colour changes in the black body as the body is heated to a temperature of 9 000 K. 🌸
7. Photograph 1 shows a communication satellite in outer space. A quantum communication attempt was performed with a laser pulse of 60 mW and a wavelength of 800 nm.



**Photograph 1**

- (a) What is the momentum of one photon from the laser pulse? 🌸
- (b) How much energy does one photon carry? 🌸
- (c) What is the number of photons per second? 🌸
- (d) What is the total momentum transferred by the laser pulse per second? 🌸

8. Complete Table 1 with information on the wavelength and photon energy for several components of waves in the electromagnetic spectrum. 🌈

Table 1

Wavelength	Photon energy	Region in the electromagnetic spectrum
500 nm		
	50 eV	
	$5.0 \times 10^{-21}$ J	

9. Figure 1 shows a photocell constructed using semiconductor material that can be activated by light with a maximum wavelength of 1 110 nm.

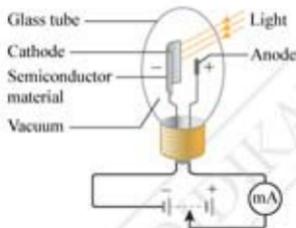


Figure 1

- (a) What is the threshold frequency and work function of the semiconductor? 🌈  
 (b) Why does the semiconductor look opaque at room temperature? 🌈
10. Muthu conducted an experiment on a grain of sand falling through a small hole. Given the mass of the grain of sand is  $5 \times 10^{-19}$  kg, the diameter of the sand is 0.07 mm, the velocity of the sand falling through the hole is  $0.4 \text{ m s}^{-1}$  and the size of the hole is 1 mm:
- (a) Estimate the de Broglie wavelength of the sand. 🌈  
 (b) Will the falling sand produce a diffraction pattern when passing through the small hole? Explain your answer. 🌈
11. When a photodiode is shone on with a red light ( $\lambda = 700 \text{ nm}$ ) and a blue light ( $\lambda = 400 \text{ nm}$ ), the maximum kinetic energy of the photoelectrons emitted by the blue light is two times that of the red light.
- (a) What is the work function of the photodiode?  
 (b) What is the threshold wavelength of the photodiode? 🌈  
 (c) What is the de Broglie wavelength of the photoelectron emitted by UV light ( $\lambda = 131 \text{ nm}$ ) from the photodiode? 🌈

## 21st Century Challenge

12. Amin conducted an experiment to determine the work function and threshold wavelength for a material  $X$ . The arrangement of the apparatus is as shown in Figure 2.

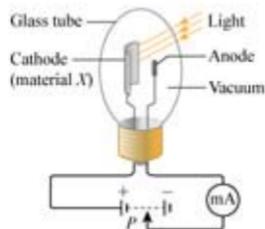


Figure 2

When the cathode coated with material  $X$  is illuminated by a light beam of wavelength,  $\lambda$ , the emitted photoelectrons will move towards the anode and give a reading in milliammeter. If the connection to the power supply is reversed, the potential difference at the anode is set to negative and that will prevent the arrival of the negatively charged photoelectrons. If the potential divider,  $P$  is adjusted until the stopping potential,  $V_s$  results in a zero milliammeter reading, then  $V_s$  is a measure of the maximum kinetic energy,  $K_{\max}$  of the photoelectrons emitted, of which  $K_{\max} = eV_s$ . Table 2 shows the experimental results for the values of  $\lambda$  and the corresponding values of  $V_s$ .

Table 2

$\lambda / \text{nm}$	$V_s / \text{V}$
135	7.53
172	5.59
227	3.98
278	2.92
333	2.06
400	1.43

- Based on Einstein's Photoelectric Equation, derive an equation that relates  $\lambda$  and  $V_s$ .
- Plot a suitable graph to determine the Planck's constant, work function and threshold wavelength for material  $X$ .
- Calculate the wavelength of light for the production of a 10.0 eV photoelectron using the work function in (b).
- What is the de Broglie wavelength for the 10.0 eV photoelectron?
- Why is material  $X$  a critical component in a night vision device?

# Answers

Scan the QR code for complete answers



<https://bit.ly/34WEgOA>

ONLY SELECTED ANSWERS ARE PROVIDED HERE

## Chapter 1 Force and Motion II

### Summative Practice

- Therefore, worker  $Y$  has to apply a force that makes an angle of  $88.58^\circ$  with the direction of the force from worker  $X$ .
- (a)  $F = 188 \text{ N}$  at an angle of  $33^\circ$  with the direction of the force applied by  $P$ .  
(b) – Advantages: The tree will fall in the direction of the resultant force. A larger angle will ensure that there is a large space between  $P$  and  $Q$ . The tree will fall on to the ground without endangering  $P$  and  $Q$ .  
– Disadvantage: The large angle between the directions of the forces produces a resultant force with a smaller magnitude.  
(c) The direction of the resultant force makes a smaller angle with the direction of the force by  $P$ . The tree will fall nearer to  $P$ . Therefore,  $P$  has to be more careful.
- $5.4933.6 \text{ N m}^{-1}$
- The resultant force of the two forces has the largest magnitude when the forces act on an object in the same direction.  
If the force  $17 \text{ N}$  and the force  $13 \text{ N}$  are in the same direction, resultant force =  $17 + 13$   
 $= 30 \text{ N}$   
The resultant force of the two forces has the smallest magnitude when the forces are in opposite directions.  
If the force  $17 \text{ N}$  and the force  $13 \text{ N}$  are in opposite directions, resultant force =  $17 + (-13)$   
 $= 4 \text{ N}$   
Therefore, the resultant forces of  $17 \text{ N}$  and  $13 \text{ N}$  has magnitude between  $4 \text{ N}$  and  $30 \text{ N}$ .
- Stage I: Resultant force =  $0 \text{ N}$   
Stage II: Resultant force =  $450 \text{ N}$  to the East  
Stage III: Resultant force =  $0 \text{ N}$

- (a) Horizontal component =  $9.83 \text{ N}$   
Vertical component =  $6.88 \text{ N}$   
(b) The horizontal component moves the knife forward.  
The vertical component pushes the knife downward.
- $T = 4.0 \text{ N}$   
 $S = 6.93 \text{ N}$

## Chapter 2 Pressure

### Summative Practice

- (a)  $A$  and  $B$  are at the same level in a stationary liquid.  
(b)  $972 \text{ kg m}^{-3}$
- (a) Pressure at point  $X$  = atmospheric pressure  
Pressure at point  $Y$  =  $0$   
(b) Since point  $X$  and point  $Z$  are at the same level, Pressure at point  $X$  = pressure at point  $Z$   
Pressure at point  $X$  = atmospheric pressure, and Pressure at point  $Z$  = pressure due to mercury column +  $0$   
Atmospheric pressure = pressure due to mercury column  
Therefore, the height of the mercury column,  $h$  is a measure of atmospheric pressure.  
(c)  $100862 \text{ Pa}$
- (a)  $800 \text{ N cm}^{-2}$   
(b) Pascal's principle  
(c) Cross-sectional area of slave cylinder  
 $= \frac{\pi \times 2.5^2}{4}$   
 $= 4.91 \text{ cm}^2$   
Braking force =  $3928 \text{ N}$
- Mass of wooden block =  $2.98 \text{ kg}$   
Weight of wooden block =  $29.23 \text{ N}$   
Buoyant force =  $31.78 \text{ N}$   
Buoyant force > weight of block  
There is a resultant force upwards  
The block moves up with an acceleration

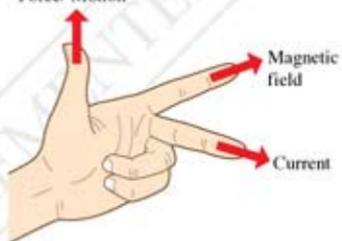
## Chapter 3 Electricity

### Summative Practice

- The filament lamps require high resistance to produce light.  
– The coiled filament causes the wire length to increase.  
– The resistance is directly proportional to the length of the wire.  
– The longer the filament wire, the higher the resistance.  
– The higher the resistance, the brighter the lamp.
- (a) (i)  $4.5 \Omega$   
(ii)  $1.33 \text{ A}$   
(iii)  $3.99 \text{ V}$   
(b) Bulb  $X$  is the brightest compared to bulb  $Y$  and bulb  $Z$ . Bulb  $Y$  and bulb  $Z$  have the same brightness.  
(c) (i)  $6 \Omega$   
(ii)  $1.0 \text{ A}$   
(iii)  $3 \text{ V}$   
(d) Bulb  $X$  and bulb  $Y$  glow with equal brightness. Bulb  $Z$  does not light up.
- (a) The electromotive force, e.m.f. is the energy transferred or work done by a source of electrical energy to move one coulomb of charge in a complete circuit.

## Chapter 4 Electromagnetism

### Summative Practice

- Fore finger: Direction of magnetic field  
Middle finger: Direction of current  
Thumb: Direction of force  
Force/Motion
- 
- (a) Induced current is the current produced in a conductor when there is relative motion between the conductor and a magnet that causes the conductor to cut magnetic field lines.  
(b)  $X$ : north pole  
 $Y$ : south pole

- (c) Figure (a): Direction of motion of magnet to the left  
Figure (b): Direction of motion of magnet to the right  
(d) Increase the number turns of the solenoid  
Increase the speed of motion of the magnet

4.  $I_s = 7.2 \text{ A}$

The loss of energy from the transformer can be neglected, that is the transformer is ideal.

7. (a)  $2.5 \text{ A}$

(b) The transformer is ideal

8.  $60.00 \%$

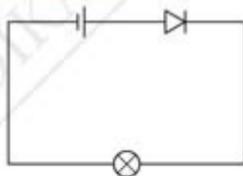
– Use laminated soft iron core

– The secondary coil is wound on top of the primary coil

## Chapter 5 Electronics

### Summative Practice

1. (a)



(b) The bulb does not light up because the diode is in reverse biased state.

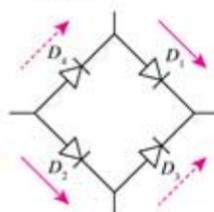
2. (a)



(b)



3. (a)



Key:

→ Positive cycle

---→ Negative cycle

(c) Half-wave rectification will occur

4. (b) Under bright conditions, LDR resistance becomes low. Therefore, the voltage across LDR decreases but the voltage across  $R$  is increased. The  $I_n$  is low and the transistor is turned off. The  $I_c$  will be low and the LED will not light up.
- (c) the LED with an alarm, the resistor with a thermistor and the LDR with a resistor.

## Chapter 6 Nuclear Physics

### Summative Practice

1. (a) A radioactive decay is a random and spontaneous process by which an unstable nucleus will decay by emitting radioactive radiation to become a more stable nucleus.
- (b) The half life,  $T_{1/2}$ , is the time taken for a sample of radioactive nuclei to decay to half of its initial number.
- (c) Nuclear energy is the energy produced by reactions in atomic nuclei.
2. (a)  $X$  is the helium nucleus or  $\alpha$ -particle,  $Y$  is  $\gamma$ -ray.
- (b) 3  $\alpha$ -particles and 2  $\beta$ -particles are released.
3. (a) 11.2 s
- (b)  $n = 5$   
so after  $5T_{1/2}$ , only 3.125% of the sample remains.
4. (a)  $A$  is the older sample. The ratio of uranium-238 to plumbum-206 is smaller.
- (b) Suppose that during the rock formation, only uranium-238 was trapped. The oldest rock formed on Earth is about 4.28 billion years. The half-life of uranium-238 is 4.5 billion years. Therefore, the decay process of uranium-238 in a rock sample has gone through less than one half-life. Hence, less than half of the uranium-238 nuclei in the sample of rock had decayed to form lead-206 nuclei. So the number of lead-206 nuclei cannot be more than the remaining uranium-238 nuclei.
6. (a) Nuclear fusion
- $${}^2_1\text{H} + {}^3_1\text{H} \rightarrow {}^4_2\text{He} + {}^1_0\text{n} + \text{energy}$$
- (b)  $2.82 \times 10^{12}$  J
8. (a) The chain reaction resulting from neutron bombardment on the uranium-235 nuclei produces a large amount of nuclear energy in the reactor.

- (b) Heat energy boils the cold water. The high pressure steam produced is capable of rotating a turbine at extremely high speed.
- (c) The rotation of a turbine switch on a dynamo which will generate electrical energy by electromagnetic induction.

## Chapter 7 Quantum Physics

### Summative Practice

1. (a) A black body is an ideal body that is able to absorb all the electromagnetic rays that fall on it.
- (b) Quantum of energy is a discrete packet of energy and not a continuous energy.
2. (a) Work function of sodium metal  
 $= 3.65 \times 10^{-19}$  J  
 Photon energy of the red light  
 $= 2.93 \times 10^{-19}$  J  
 Photoelectric effect does not occur because of the photon energy of the red light is lower than work function of sodium metal.
- (b) 545 nm
3.  $6.93 \times 10^{27}$  J
4. (a)  $1.19 \times 10^{-27}$  kg m s<sup>-1</sup>
- (b)  $1.40 \times 10^{16}$  s<sup>-1</sup>
5. (a) Louis de Broglie hypothesized that particles such as electrons could have wave properties.  
 de Broglie wavelength,  $\lambda_e = \frac{h}{p}$   
 $p$  is the electron momentum
- (d)  $2.41 \times 10^{-19}$  J
6. (a) The rays of light that enter the large cavity will undergo repeated reflections on the inner walls of the cavity. At each reflection, part of the rays are absorbed by the inner walls of the cavity. Reflections continue to occur until all the rays are absorbed and none of them can leave the cavity. Thus, the cavity acts like a black body.
7. (a)  $8.29 \times 10^{-28}$  kg m s<sup>-1</sup>
- (b)  $2.49 \times 10^{-19}$  J
- (c)  $2.41 \times 10^{17}$  s<sup>-1</sup>