

CHAPTER IV : QUANTUM PHYSICS

Formative Practice 7.1 [Quantum Theory of Light]

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.

$$h = 6.63 \times 10^{-34} \text{ Js} \quad c = 3.00 \times 10^8 \text{ ms}^{-1} \quad m_e = 9.11 \times 10^{-31} \text{ kg} \quad 1.00 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

Formative Practice 7.2 [Photoelectric Effect]

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?
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$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$c = 3.00 \times 10^8 \text{ ms}^{-1}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$1.00 \text{ eV} = 1.60 \times 10^{-19}$$

Formative Practice 7.3 [Einstein's Photoelectric Theory]

1. (a) State Einstein's Photoelectric Equation.

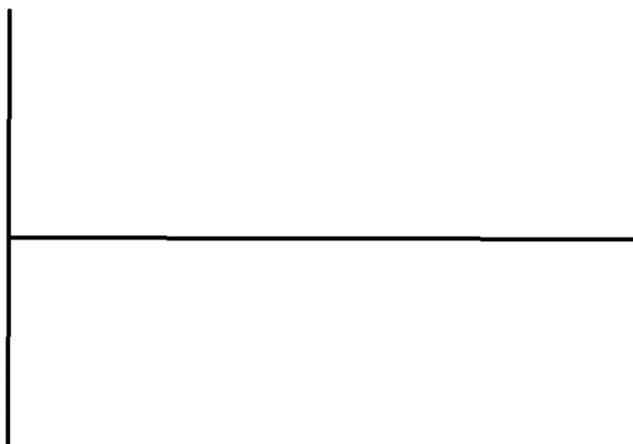
(b) State the meaning of:

(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)?

$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$c = 3.00 \times 10^8 \text{ ms}^{-1}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$1.00 \text{ eV} = 1.60 \times 10^{-19}$$

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.

$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$c = 3.00 \times 10^8 \text{ ms}^{-1}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$1.00 \text{ eV} = 1.60 \times 10^{-19}$$

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.

(a) What is the momentum of one photon from the laser pulse?



Photograph 1

(b) How much energy does one photon carry?

(c) What is the number of photons per second?

$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$c = 3.00 \times 10^8 \text{ ms}^{-1}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$1.00 \text{ eV} = 1.60 \times 10^{-19}$$

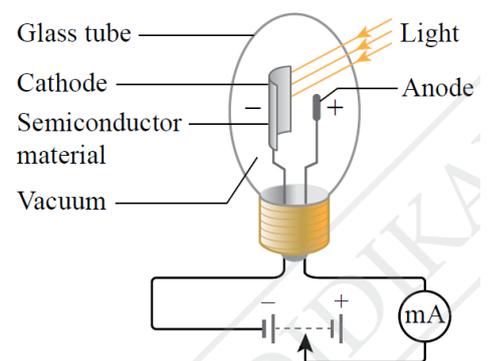
(d) What is the total momentum transferred by the laser pulse per second?

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

Wavelength, λ	Photon energy, E	Region of the electromagnetic spectrum
500 nm		
	50 eV	
	5.0×10^{-21} J	

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

(a) What is the threshold frequency and work function of the semiconductor?



(b) Why does the semiconductor look opaque at room temperature?

$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$c = 3.00 \times 10^8 \text{ ms}^{-1}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$1.00 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

10. Muthu conducted an experiment on a grain of sand falling through a small hole. Given the mass of the grain of sand is 5×10^{-10} kg, the diameter of the sand is 0.07 mm, the velocity of the sand falling through the hole is 0.4 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? 🧠

$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$c = 3.00 \times 10^8 \text{ ms}^{-1}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$1.00 \text{ eV} = 1.60 \times 10^{-19}$$

- (c) What is the de Broglie wavelength of the photoelectron emitted by UV light ($\lambda = 131 \text{ nm}$) from the photodiode? 🧠

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.

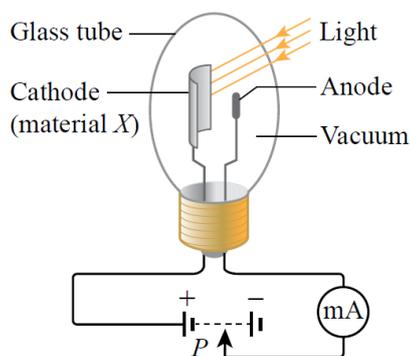


Figure 2

Table 2

λ / nm	V_s / V
135	7.53
172	5.59
227	3.98
278	2.92
333	2.06
400	1.43

When the cathode coated with material X is illuminated by a light beam of wavelength, λ , 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 $K_{\text{max}} = eV_s$. Table 2 shows the experimental results for the values of λ and the corresponding values of V_s .

- (a) Based on Einstein's Photoelectric Equation, derive an equation that relates λ and V_s .

$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$c = 3.00 \times 10^8 \text{ ms}^{-1}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$1.00 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

(b) Plot a suitable graph to determine the Planck's constant, work function and threshold wavelength for material X. 🧠

(c) Calculate the wavelength of light for the production of a 10.0 eV photoelectron using the work function in (b). 🧠

(d) What is the de Broglie wavelength for the 10.0 eV photoelectron? 🧠

(e) Why is material X a critical component in a night vision device? 🧠

$$h = 6.63 \times 10^{-34} \text{ Js}$$

$$c = 3.00 \times 10^8 \text{ ms}^{-1}$$

$$m_e = 9.11 \times 10^{-31} \text{ kg}$$

$$1.00 \text{ eV} = 1.60 \times 10^{-19}$$

hidup kesepian tanpa kasih, cukup sekian dan terima kasih

Formative Practice 7.1

- Speed of light in vacuum, $c = 3.00 \times 10^8 \text{ m s}^{-1}$
Wavelength, $\lambda = 10 \text{ nm}$
 $= 10 \times 10^{-9} \text{ m}$
Planck's constant, $h = 6.63 \times 10^{-34} \text{ J s}$
Frequency, $f = \frac{c}{\lambda}$
 $= \frac{3.00 \times 10^8}{10 \times 10^{-9}}$
 $= 3.0 \times 10^{16} \text{ Hz}$
Energy, $E = hf$
 $= (6.63 \times 10^{-34})(3.0 \times 10^{16})$
 $= 1.99 \times 10^{-17} \text{ J}$

- Photon power, $P = 50 \text{ W}$
Planck's constant, $h = 6.63 \times 10^{-34} \text{ J s}$
Frequency of green light, $f = 5.49 \times 10^{14} \text{ Hz}$
 $P = nhf$
Number of photons emitted per second, $n = \frac{P}{hf}$

- (a) de Broglie wavelength,
 $E = \frac{1}{2}mv^2$
 $mv = \sqrt{2mE}$
 $\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2mE}}$
 $= \frac{6.63 \times 10^{-34}}{\sqrt{2(9.11 \times 10^{-31})(50 \times 1.60 \times 10^{-19})}}$
 $= 1.74 \times 10^{-10} \text{ m}$

(b) Electron diffraction

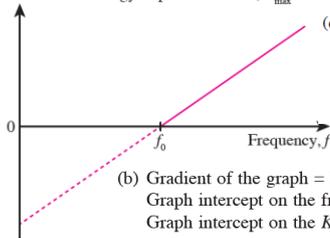
Formative Practice 7.2

- Emission of electrons from a metal surface when shone on by light of a certain frequency.
- Yes. The number of photoelectrons emitted depends on the number of photons that arrive on the metal surface.
- The higher the frequency of the light photons, the higher the kinetic energy of the photoelectrons emitted from the metal surface.
The minimum frequency of light needed for a metal to emit electrons is the threshold frequency, f_0 for the metal.
The kinetic energy of photoelectrons does not depend on the intensity of light.
Photoelectrons are emitted instantaneously when shone on by light.
- Light consists of discrete energy packets, when a photon hits a metal surface, all its energy will be transferred to an electron in the metal. With this, the photoelectron will be emitted instantaneously from the metal surface if the frequency of light is higher than the threshold frequency of the metal.
- No. The intensity of light only affects the number of photons arriving on the metal per second (photon rate). The maximum kinetic energy of a photoelectron is influenced by the photon energy. Increasing the light intensity will not increase the kinetic energy of the photoelectrons.

Formative Practice 7.3

- (a) $hf = W + \frac{1}{2}mv_{\text{max}}^2$
(i) Work function, W is the minimum energy required for a photoelectron to be emitted from a metal surface.
(ii) Threshold frequency, f_0 is the minimum frequency for a light photon to produce photoelectric effect.
(iii) $W = hf_0$

- (a) Maximum kinetic energy of photoelectrons, K_{max}

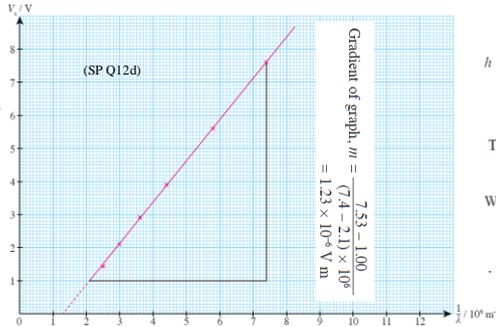


- (b) Gradient of the graph = Planck's constant, h
Graph intercept on the frequency axis = threshold frequency of the metal, f_0
Graph intercept on the K_{max} axis = work function of the metal, W

- Work function, $W = 4.32 \times 10^{-19} \text{ J}$
Wavelength, $\lambda = 4 \times 10^{-7} \text{ m}$
Planck's constant, $h = 6.63 \times 10^{-34} \text{ J s}$
Speed of light in vacuum, $c = 3.00 \times 10^8 \text{ m s}^{-1}$
 $hf = W + K_{\text{max}}$
then $c = \lambda f$ or $f = \frac{c}{\lambda}$
So, $\frac{hc}{\lambda} = W + K_{\text{max}}$
 $K_{\text{max}} = \frac{hc}{\lambda} - W$
 $= \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{4 \times 10^{-7}} - 4.32 \times 10^{-19}$
 $= 6.53 \times 10^{-20} \text{ J}$

Summative Practice

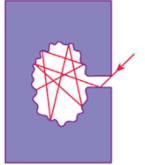
- (a) A black body is an ideal body that is able to absorb all the electromagnetic rays that fall on it.
(b) Quantum of energy is a discrete packet of energy and not a continuous energy.
- (a) Work function of sodium metal = 2.28 eV
 $= 2.28 \times 1.60 \times 10^{-19}$
 $= 3.65 \times 10^{-19} \text{ J}$
Photon energy of the red light = $\frac{hc}{\lambda}$
 $= \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{680 \times 10^{-9}}$
 $= 2.93 \times 10^{-19} \text{ J}$
Photoelectric effect does not occur because of the photon energy of the red light is lower than work function of sodium metal.
(e) For a night vision device, X should have a threshold wavelength longer than that of visible light ($4 \sim 7 \times 10^{-7} \text{ m}$).
 X has a threshold wavelength of $7.69 \times 10^{-7} \text{ m}$ so it can be activated by radiation outside the wavelength of visible light and function in the dark.



- (a) Louis de Broglie hypothesised that particles such as electrons could have wave properties.

- de Broglie wavelength, $\lambda_e = \frac{h}{p}$
 p is the momentum of the electron
(b) Momentum of the electron, $p = \frac{h}{\lambda}$
(d) $\lambda = \frac{h}{\sqrt{2mE}}$
 $\lambda^2 = \frac{h^2}{2mE}$ or $E = \frac{1}{2}mv^2$
 $= \frac{1}{2}(9.11 \times 10^{-31})(7.28 \times 10^5)^2$
 $= 2.41 \times 10^{-19} \text{ J}$
Kinetic energy of the electron, $E = \frac{h^2}{2m\lambda^2} = 2.41 \times 10^{-19} \text{ J}$

- (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.
(b) As the temperature of the black body increases, the intensity of the radiation emitted increases rapidly. The intensity of the violet-blue rays increases more than the orange-yellow rays. Therefore, the black body is violet-blue at 9 000 K.



- (a) $p = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{800 \times 10^{-9}} = 8.29 \times 10^{-28} \text{ kg m s}^{-1}$
(b) The energy carried by each photon, $E = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{800 \times 10^{-9}} = 2.49 \times 10^{-19} \text{ J}$
(c) Number of photons per second, $n = \frac{P}{E} = \frac{60 \times 10^{-3}}{2.49 \times 10^{-19}} = 2.41 \times 10^{17} \text{ s}^{-1}$

- (d) Total momentum per second = momentum of one photon \times number of photons per second
 $= 8.29 \times 10^{-28} \times 2.41 \times 10^{17}$
 $= 2.0 \times 10^{-10} \text{ kg m s}^{-2}$

8.

Wavelength, λ	Photon energy, E	Region of the electromagnetic spectrum
500 nm	2.5 eV ($3.98 \times 10^{-19} \text{ J}$)	Visible light
25 nm ($2.49 \times 10^{-8} \text{ m}$)	50 eV	Ultraviolet
40 μm ($3.98 \times 10^{-5} \text{ m}$)	$5.0 \times 10^{-21} \text{ J}$	Infrared

- (a) $f_0 = \frac{c}{\lambda_0}$
 $= \frac{3.00 \times 10^8}{1.110 \times 10^{-9}} = 2.70 \times 10^{14} \text{ Hz}$
 $W = hf_0 = (6.63 \times 10^{-34})(2.70 \times 10^{14}) = 1.79 \times 10^{-19} \text{ J}$

- (b) At room temperature, the thermal energy is insufficient to release electrons in a photocell or to activate the photocell.

- (a) $\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{(5 \times 10^{-19})(0.4)} = 3.32 \times 10^{-24} \text{ m}$

- (b) No. The de Broglie wavelength of the sand is too short (10^{-24} m) compared to the size of the hole (1 mm). If the size of the hole is further reduced to approximate the order of the de Broglie wavelength, the sand will not be able to pass through it because the diameter of the sand is 0.07 mm.

- (a) Work function, W

$$hf = W + K$$

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

$$\frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{700 \times 10^{-9}} = W + K \quad \dots(1)$$

$$\frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{400 \times 10^{-9}} = W + 2K \quad \dots(2)$$

$$2 \times (1) - (2): W = 2 \times \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{700 \times 10^{-9}} - \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{400 \times 10^{-9}}$$

$$= 7.10 \times 10^{-20} \text{ J}$$

- (b) Threshold wavelength, λ_0

$$\frac{hc}{\lambda_0} = W$$

$$\lambda_0 = \frac{hc}{W} = \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{7.10 \times 10^{-20}} = 2.80 \times 10^{-6} \text{ m}$$

- (a) Based on Einstein's Photoelectric Equation,

$$hf = W + K_{\text{max}}$$

$$hf = W + eV_s, W = \frac{hc}{\lambda_0}$$

$$\frac{hc}{\lambda} - \frac{hc}{\lambda_0} = eV_s$$

$$eV_s = h\left(\frac{c}{\lambda} - \frac{c}{\lambda_0}\right)$$

$$V_s = \frac{hc}{e}\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)$$

(b)

λ / nm	V_s / V	$\frac{1}{\lambda} / 10^6 \text{ m}^{-1}$
135	7.53	7.4
172	5.59	5.8
227	3.98	4.4
278	2.92	3.6
333	2.06	3.0
400	1.43	2.5

$$3. \text{ de Broglie wavelength, } \lambda_e = \frac{h}{p}$$

$$= \frac{h}{\sqrt{2meV}}$$

$$= \frac{h}{\sqrt{2 \times 9.11 \times 10^{-31} \times K}}$$

$$590 \times 10^{-9} = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.11 \times 10^{-31} \times K}}$$

$$K = \frac{(6.63 \times 10^{-34})^2}{2 \times 9.11 \times 10^{-31} \times (590 \times 10^{-9})^2}$$

$$= 6.93 \times 10^{-25} \text{ J}$$

- (a) Momentum = $\frac{h}{\lambda}$
 $= \frac{6.63 \times 10^{-34}}{555 \times 10^{-9}}$
 $= 1.19 \times 10^{-27} \text{ kg m s}^{-1}$
(b) $P = \frac{nhc}{\lambda}$
 $n = \frac{P\lambda}{hc}$
 $= \frac{(5.00 \times 10^{-3})(555 \times 10^{-9})}{(6.63 \times 10^{-34})(3 \times 10^8)}$
 $= 1.40 \times 10^{16} \text{ s}^{-1}$

- (c) Velocity of the electron, $v = \frac{p}{m}$
 $= \frac{6.63 \times 10^{-25}}{9.11 \times 10^{-31}}$
 $= 7.28 \times 10^5 \text{ m s}^{-1}$

(c) de Broglie wavelength, λ_p

$$\frac{hc}{\lambda} = W + K_{\text{max}}$$

$$\frac{hc}{\lambda} - W = K_{\text{max}} = \frac{1}{2}mv^2$$

$$= \frac{1}{2}m\left(\frac{h}{m\lambda}\right)^2$$

$$= \frac{1}{2} \times \frac{h^2}{m\lambda^2}$$

$$= \frac{1}{2} \times \frac{h^2}{m\lambda^2} = \frac{1}{2} \times \frac{(6.63 \times 10^{-34})^2}{9.11 \times 10^{-31} \times \lambda^2}$$

$$= \frac{1}{2} \times \frac{4.38 \times 10^{-67}}{9.11 \times 10^{-31} \times \lambda^2} = \frac{2.39 \times 10^{-37}}{\lambda^2}$$

$$= \frac{2.39 \times 10^{-37}}{\lambda^2} = 1.48 \times 10^{-19} \text{ J}$$