QUANTUM PHYSICS

22 Quantum physics

22.1 Energy and momentum of a photon

Candidates should be able to:

1. understand that electromagnetic radiation has a particulate nature
2. understand that a photon is a quantum of electromagnetic energy
3. recall and use $E = hf$
4. use the electronvolt (eV) as a unit of energy
5. understand that a photon has momentum and that the momentum is given by $p = E / c$

Photon:

Discrete — Can be counted / Integer multiple

Def. Discrete packet or quantum of energy of electromagnetic radiation identified by $E = hf$ is photon

Energy of a photon:- $E \propto f$

$$E = hf$$

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

Also, speed of e.m. waves, $v = c = 3.00 \times 10^{8}\ ms^{-1}$

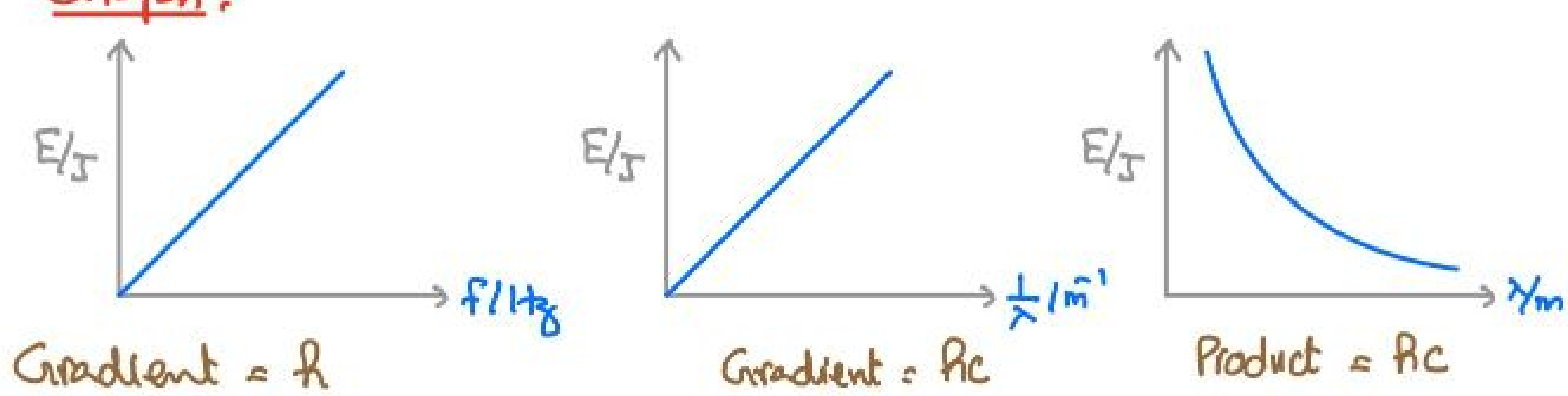
$$c = f\lambda \Rightarrow f = \frac{c}{\lambda}$$

Therefore,

$$E = \frac{hc}{\lambda} \Rightarrow E = \frac{\text{Constant}}{\lambda}$$

$$E \propto \frac{1}{\lambda}$$

Graph:



Relative order:

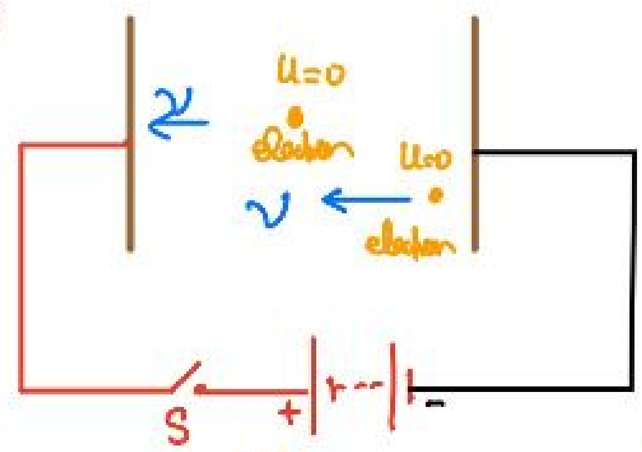
← f/Hz or E/J

Gamma rays	X-rays	U.V	Visible light	Infra red	Microwave	Radio wave

λ/m →

Electron volt:

Concept:



$F = ma$

$Eq = ma$

$$V = \frac{W}{q} \Rightarrow V = \frac{E_K}{q}$$

$$Vq = E_K$$

$$eV = E_K$$

$$1eV = (1V)(1.60\times10^{-19}) = 1.60\times10^{-19} J$$

Def It is the kinetic energy gained by an electron which is accelerated through a p.d. of 1 volt.

Symbol: eV

Value $1eV = 1.60\times10^{-19} J$

Note: To convert

(i) eV to Joule (J), multiply by 1.60×10^{-19}

(ii) J to eV, divide by 1.60×10^{-19}

Relationship b/w Energy and momentum of a photon:-

$$E = mc^2$$

$$E = (mc)c$$

$$E = (p)c \Rightarrow \boxed{p = \frac{E}{c}}$$

p - momentum = mv

Nature of photon :-

→ Particle nature
→ Wave nature

Particle model :

Identification :- A particle is a hard object, have mass and move about according to the Newton's laws.

Example :

Example	Model	Macroscopic view
Electricity	flow of charge carrier / electron	current
Solid	crystalline orientation	S. H. M.
Gases	Kinetic theory	Pressure, volume and temperature.
Radioactivity	nuclear model of an atom	Radioactive decay, Nuclear reaction

Wave model :-

Identification : Waves do not have any mass or charge but are composed of wavelength which vary while passing through different mediums

Example	Varying quantities
Electromagnetic waves	wave travel perpendicularly to both mutually perpendicular Electric and magnetic field as per Flemming's left hand rule
Waves on a string	displacement
Sound	pressure / Density

22.2 Photoelectric effect

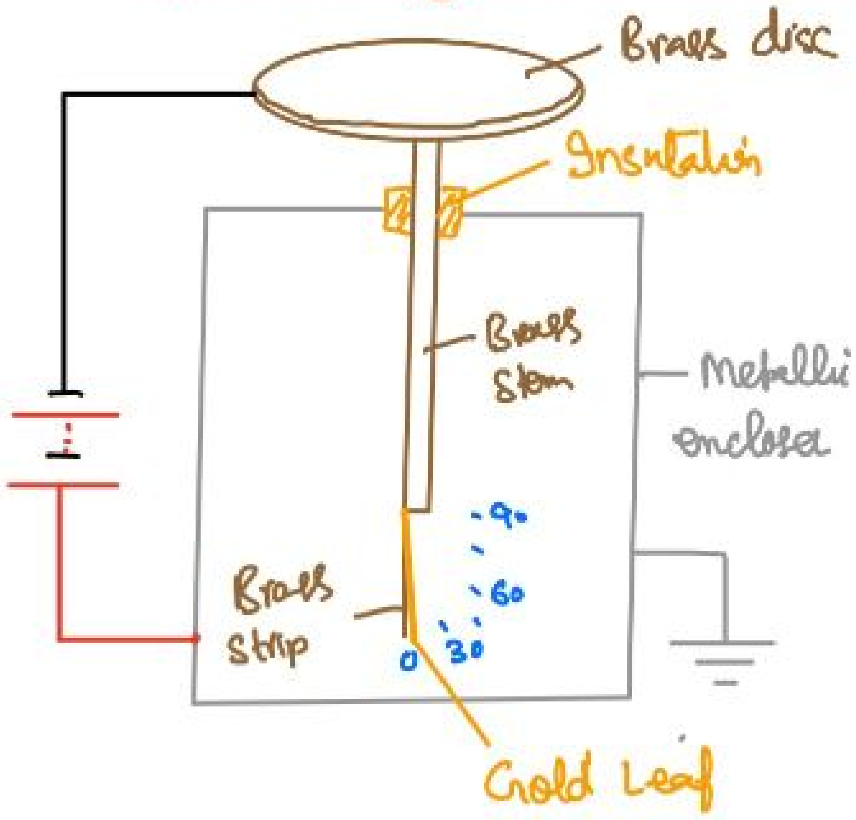
Candidates should be able to:

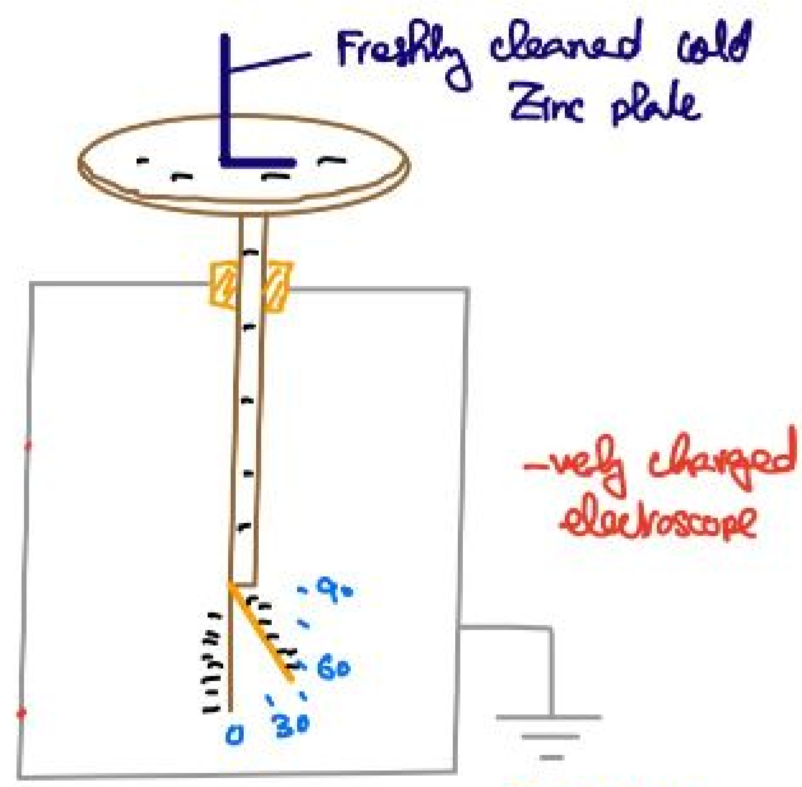
1. understand that photoelectrons may be emitted from a metal surface when it is illuminated by electromagnetic radiation
2. understand and use the terms threshold frequency and threshold wavelength
3. explain photoelectric emission in terms of photon energy and work function energy
4. recall and use $hf = \Phi + \frac{1}{2}mv_{max}^2$
5. explain why the maximum kinetic energy of photoelectrons is independent of intensity, whereas the photoelectric current is proportional to intensity

Photoelectric effect:-

Def. The emission of electrons from the surface of cold metal when electromagnetic radiations of sufficient frequency are incident on it.

Exp. to study that electrons are emitted in photoemission:-





$F \propto Q_1 Q_2$
↓

Observational analysis:-

S.No.	UV	Deflection of Gold leaf	Photo-emission
1.	OFF	Constant ie 22°	No
2.	ON	decreases to 14°	Yes
3.	OFF	Remain constant at 14°	No
4.	ON	Further decreases to 9°	Yes

Deflecting angle decreases only when Zinc plate is exposed to Ultra-violet photons.

Reason: Photons remove electrons from Zinc plate leaving behind +ve charges on it. These +ve charges are neutralised by -ve charges at Brass strip and Gold leaf. So decreases in the strength of -ve charges decreases the Coulomb's repulsive force and deflecting angle also decreases.

Note: No significant change is observed if same experiment is repeated with a +vely charged electroscope.

Result: Only electrons are emitted in photoelectric effect and are known as photo-electrons.

Characteristics of photoelectric effect:-

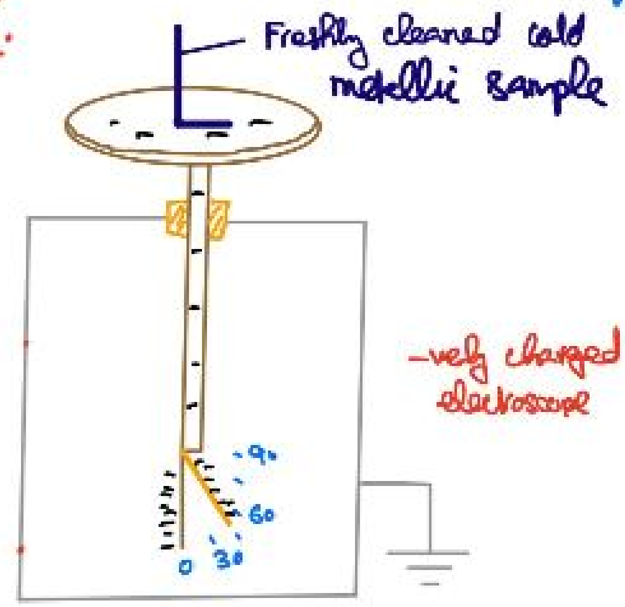
(1) Photo-emission depends upon threshold frequency:-

Def. The minimum frequency of incident photons required to release electrons from the surface of metal.

Symbol: f_0

Dependance Nature of material

Exp.



Relative order:

$\longleftarrow$ f/Hz or E/J

Gamma rays	X-Rays	U.V	Visible light	Infrared	Microwave	Radio wave

λ/m $\longrightarrow$

S.No.	Metallic Sample	e.m. radiations	Deflection of Electroscope	Photo-emission
1.	Zinc	Gamma rays, X-Rays	Decreases	Yes
2.	Zinc	UV	//	//
3.	Zinc	Visible	Remain constant	No
4.	Zinc	Microwave Radio wave	//	//
5.	Caesium	γ-Rays, X-Rays, UV	Decreases	Yes
6.	Caesium	Visible	//	//
7.	Caesium	Microwave	Remain constant	No
8	Caesium	Radio wave	//	No

Result

$(f_0)_{Zn} > (f_0)_{Cs}$

$(f_0)_{Zn}$ ↙ UV

$(f_0)_{Cs}$ ↓ Visible light

Result: Threshold frequency of Zinc is greater than threshold frequency of Caesium ie

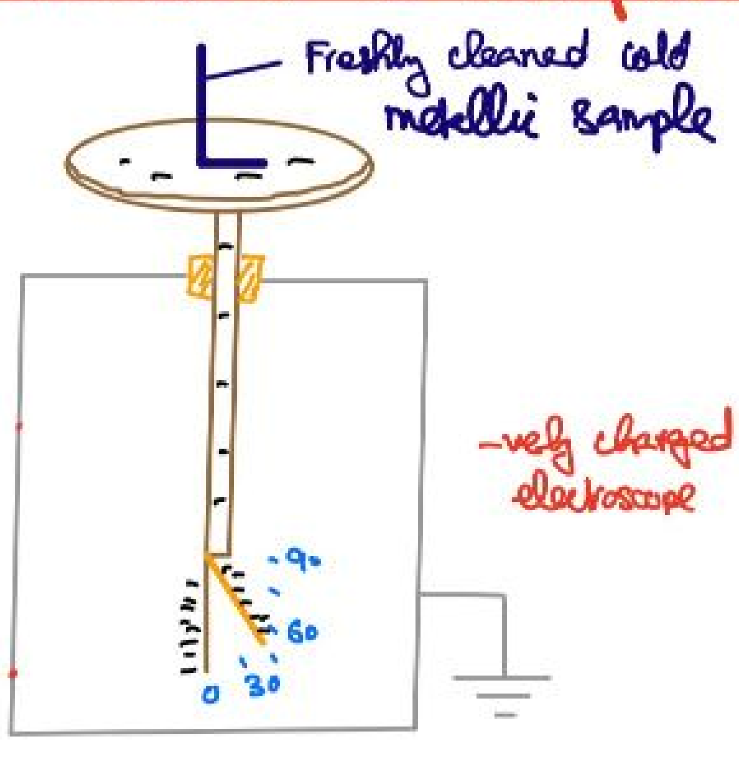
$$(f_0)_{Zn} > (f_0)_{Cs}$$

i.e electrons of Zinc need greater energy to be ejected out as compared to Caesium.

(2) Photo-emission is an instantaneous process:-

Electrons emit instantaneously if a metal is exposed to incident photon with frequency equal to or greater than the threshold level of metal i.e there is no time delay between incidenting photons and emission of photoelectrons unlike thermionic emission. This property therefore defines particle nature of e.m. radiation.

(3) Photo-emission is independent of Intensity:-



Relative order:

← f/Hz or E/J

Gamma rays	X-rays	U.V	visible light	Infra red	Microwave	Radio wave

λ/m →

Observational Analysis:-

S.No.	Metallic Sample	Frequency of Photons	Power of Source	Deflecting angle
1.	Zinc	Radio wave	20W	No change
2.	Zinc	//	1200 W	//
3.	Zinc	Microwaves and Light waves	20W	//
4.	Zinc	//	12000W	//
5.	Zinc	UV	2W	decrease
6.	Zinc	UV	20W	Sharp decrease
7.	Zinc	Gamma rays or X-ray	2W	decrease
8	Zinc	//	20W	Very sharp decrease

The increase in Power rating of source signify that no. of photons emitted from that source is increased without changing the frequency of single photon.

Result: No photo-emission occur if the frequency of source/e.m radiations is less than threshold frequency of metal, what so ever is the intensity of source is (i.e no. of photons incident per unit time per unit perpendicular area).

(4) Einstein's equation of photoelectric effect:-

By Principle of conservation of energy

Energy of a Photon = Minimum energy required to remove electron from a metal surface + K.E. of emitted Photoelectrons.

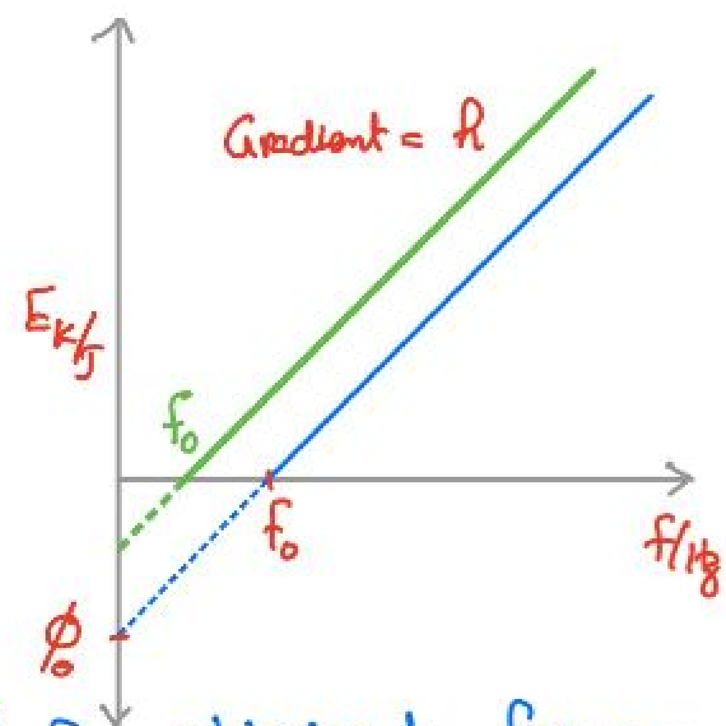
$$E = \text{work function} + E_K$$

$$E = \phi_0 + E_K$$

$$hf = hf_0 + E_K$$

$$E_K = hf - hf_0$$

$$y = mx + c$$



Gradient ⟶ Planck's constant

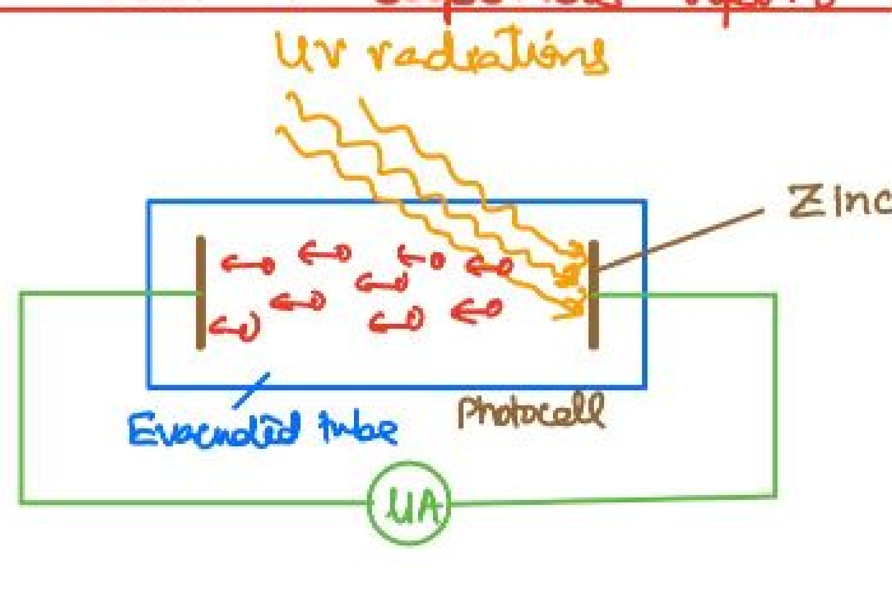
X-intercept ⟶ Threshold frequency

Y-intercept ⟶ work function

Note: Same trend of graph is obtained for any other metal (ie same Gradient) if its threshold frequency is less with less -ve y-intercept shown by Green line in graph

(5) Photoelectric current depends upon intensity of Photons:

Exp.



Observational Analysis:

S.No.	Photons	Power rating of source	I / μA	Reason
1.	UV	Constant (low)	detect	$hf = hf_0 + E_K$ ie K.E. of Photoelectrons define current
2.	UV	↑	↑	(no. of photons) ∝ (no. of electrons) emitted per unit time ↑
3.	UV	↑↑	↑↑	Same as in S.No.2
4.	X-rays	Constant (low)	detect	K.E. of photoelectrons define current
5.	X-ray	↑	↑	(K.E) ↑ in comparison with (UV) and no. of (photons) ∝ (no. of electrons) ↑

$$\text{Intensity} = \frac{\frac{\text{Total energy}}{\text{time}}}{\text{Perpendicular area}}$$

$$\text{Intensity} = \frac{(\text{no. of photons})(\text{Energy of a single photon})}{(\text{time})(\text{Area})}$$

$$I = \frac{nE}{tA}$$

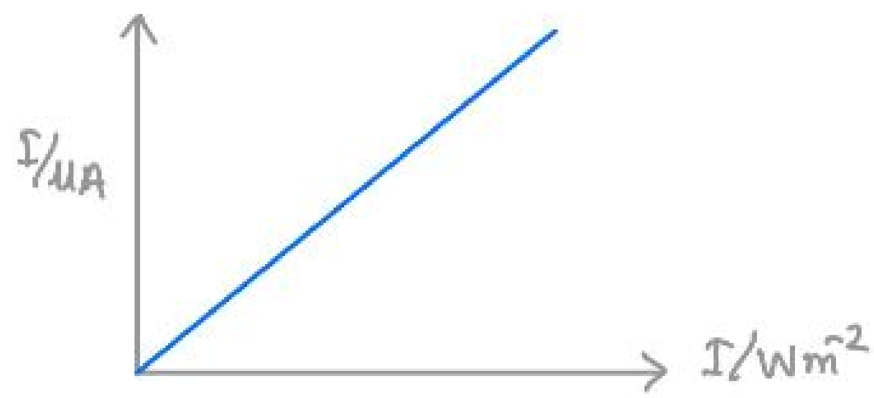
i.e (Intensity) ↑ if

(i) n ↑ i.e (no. of photons from a source is increased by increasing its power rating).

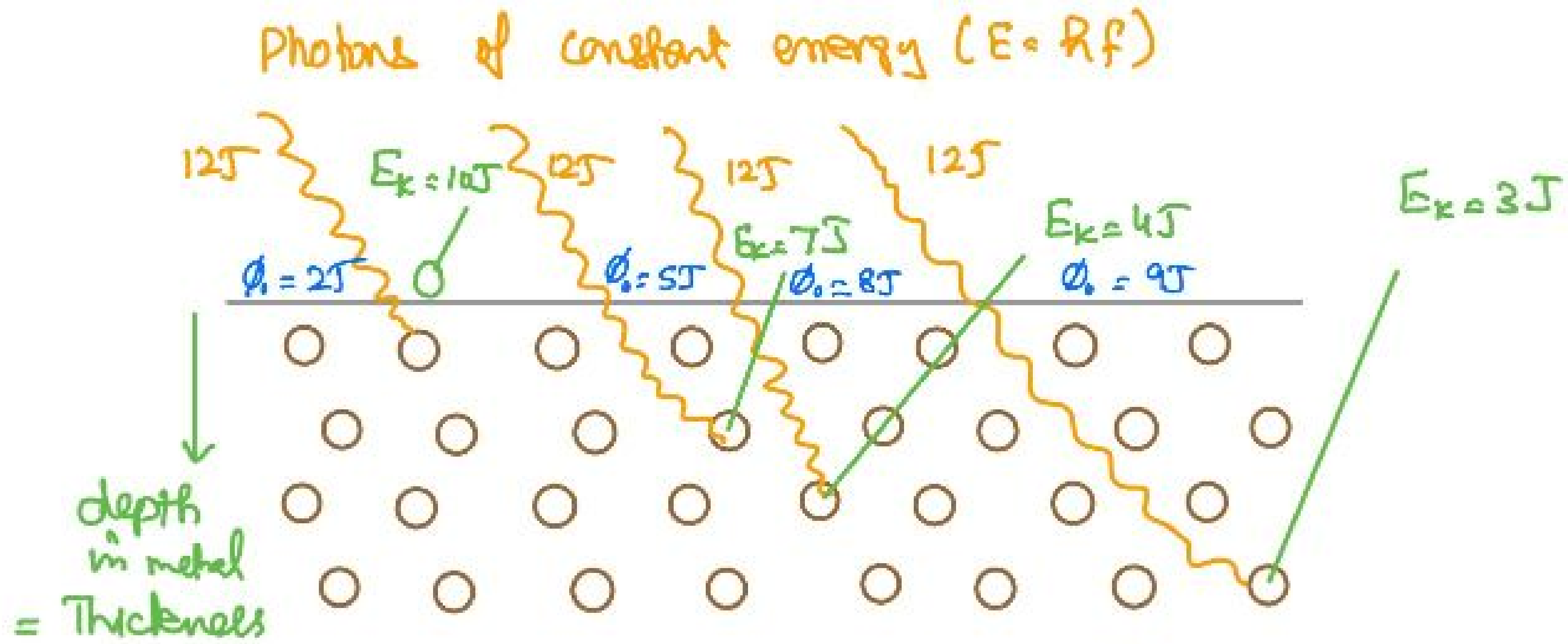
(ii) E ↑ i.e (Energy of a photon is increased by replacing it with a source having higher frequency).

Result:- Photoelectric current increases directly with the increase of intensity of photons.

ie $I/\mu A \propto I/Wm^{-2}$

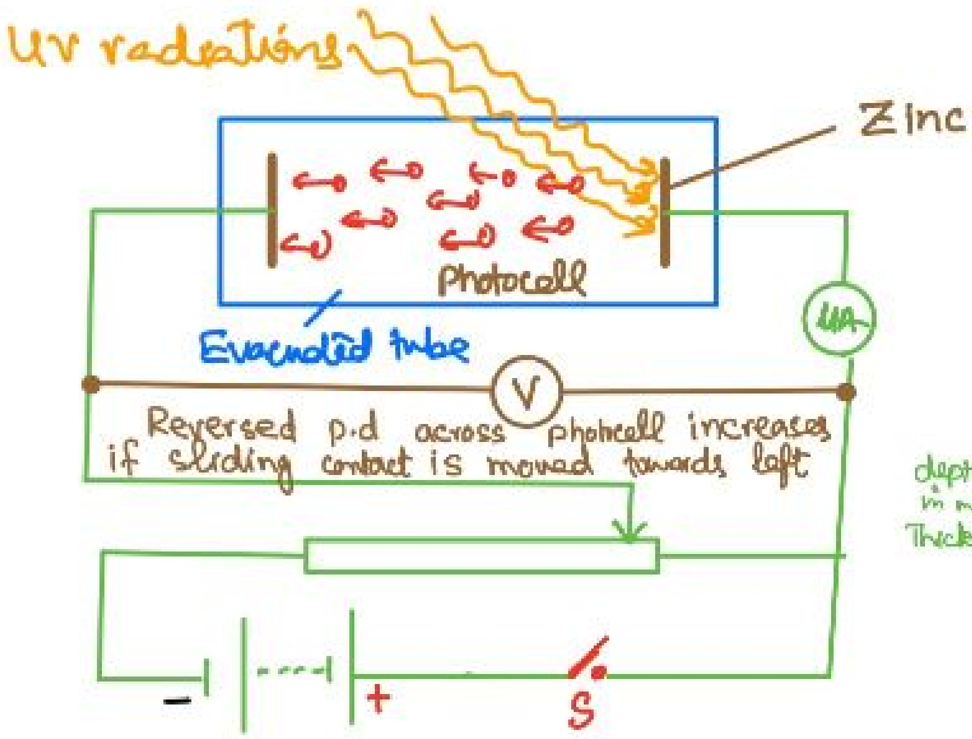


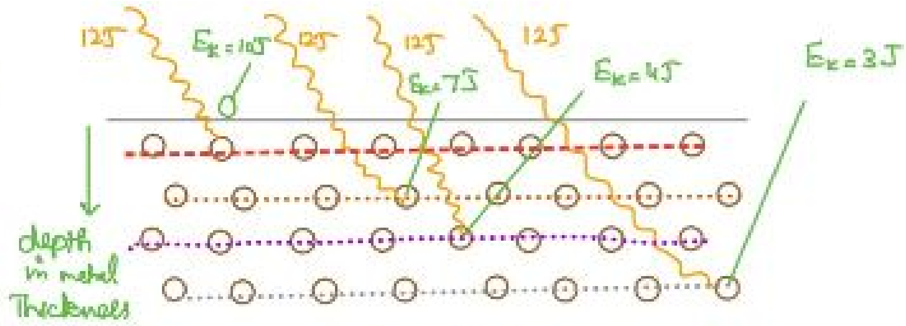
(6) Kinetic energy of photoelectrons:-



Electrons emitted from the metal have a range of Kinetic energies. Maximum Kinetic energy correspond to electrons emitted from the surface. Other electrons have lesser energy depending upon depth from where they are emitted out.

Maximum K.E. of photoelectrons can be determined by checking its ability to move against an electric force. So a reversed battery is connected across a photocell as shown.





$$I = \frac{ne}{t}$$

Observation: With the increase of reversed potential, photoelectric current decreases because few photoelectrons do not possess sufficient kinetic energy to do work against repulsive forces to complete the circuit. The photoelectric current becomes zero at a certain maximum reversed potential, also called stopping potential. This corresponds to the maximum initial kinetic energy with which the photoelectrons are emitted.

Loss of kinetic energy = Gain in Electric potential energy

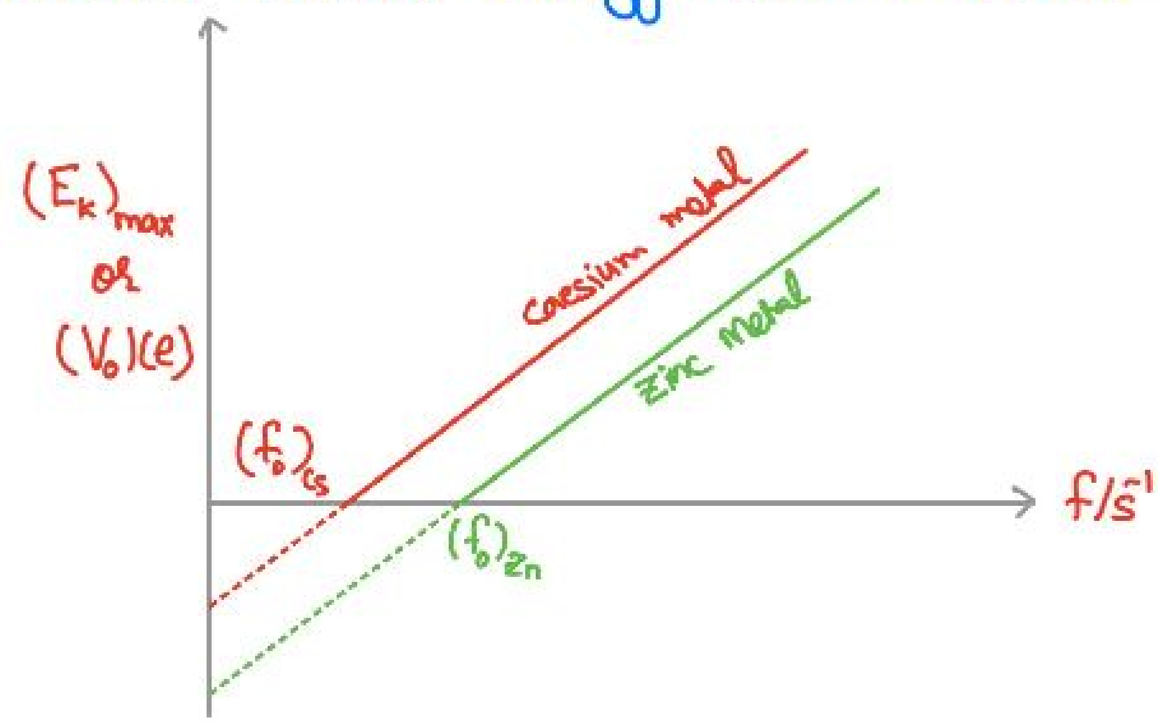
$$(E_k)_{max} = (V_0)(e)$$

Results:

1- Current decreases with the increase of reversed stopping potential indicates that there is a range of kinetic energies of emitted photoelectrons.

2- If this experiment is repeated with e.m. radiations of greater intensity but same frequency, the maximum current detected by micro-ammeter increases but the value of stopping potential (V_0) is unchanged.

3- If frequency of the incident radiations is increased, the maximum kinetic energy also increases.



Results of photo-electric effect :-

Q.9(a)/J-14/41 and 43
Q.8(b)/N-12/41 and 42
Q.7/N-08

Photo-electric effect provides particulate nature of e.m. radiations on the basis of following evidences:

1- No photo-emission occur if frequency of photons is less than threshold level of metal.

2- Photo-emission is an instantaneous process.

3- Rate of emission of electrons depends upon intensity.

4- Maximum kinetic energy of photoelectrons is independent of intensity but dependent on frequency.

5- Photoelectric current depends directly on intensity

7 Some data for the work function energy Φ and the threshold frequency f_0 of some metal surfaces are given in Fig. 7.1.

For Examiner's Use

metal	$\Phi / 10^{-19}$ J	$f_0 / 10^{14}$ Hz
sodium	3.8	5.8
zinc	5.8	8.8
platinum	9.0	

Fig. 7.1

(a) (i) State what is meant by the *threshold frequency*.

Minimum frequency of incident photons that can cause photoemission process.

.... [2]

(ii) Calculate the threshold frequency for platinum.

Work function, $\phi_0 = h f_0$

$9.0\times10^{-19} = (6.63\times10^{-34}) f_0$

$f_0 = 1.36\times10^{15}$ Hz

$\frac{\Phi_{Pt}}{\Phi_{Zn}} = \frac{h f_0}{h f_1}$

$\frac{9.0\times10^{-19}}{5.8\times10^{-19}} = \frac{f_0}{8.8\times10^{14}}$

threshold frequency = ... Hz [2]

(b) Electromagnetic radiation having a continuous spectrum of wavelengths between 300 nm and 600 nm is incident, in turn, on each of the metals listed in Fig. 7.1.
Determine which metals, if any, will give rise to the emission of electrons.

$\lambda = 300$ nm : $c = f\lambda \Rightarrow f = \frac{c}{\lambda} = \frac{3.00\times10^{8}}{300\times10^{-9}} = 1.0\times10^{15}$ Hz

$\lambda = 600$ nm : $c = f\lambda \Rightarrow f = \frac{3.00\times10^{8}}{600\times10^{-9}} = 5.0\times10^{14}$ Hz

Given frequencies are in the range to emit electron from Sodium and Zinc

[2]

(c) When light of a particular intensity and frequency is incident on a metal surface, electrons are emitted.
State and explain the effect, if any, on the rate of emission of electrons from this surface for light of the same intensity and higher frequency.

Intensity = $\frac{(\text{no. of photons})(\text{Energy of a photon})}{(\text{time})(\text{Area})}$

$I = \frac{(n)(hf)}{(t)(A)}$

As I = Constant, $(\frac{n}{t})\downarrow$ if $f\uparrow$ as h = Constant [3]

So few electrons are emitted per unit time.

6 (a) Explain what is meant by a *photon* of electromagnetic radiation.

Discrete packet or quantum of energy of e.m. radiations identified by $E = hf$ is photon. [2]

(b) The photoelectric effect provides evidence for the particulate nature of electromagnetic radiation. State three experimental observations that support this conclusion.

1. ....

2. ....

3. .... [3]

(c) Electromagnetic radiation of wavelength λ and intensity I, when incident on a metal surface, causes n electrons to be ejected per unit time. The maximum kinetic energy of the electrons is E_{max}.

$I = \frac{nE}{tA}$ $\quad E = hf = \frac{hc}{\lambda}$

$E = \phi_0 + E_k$

$hf - hf_0 = (E_k)_{max}$

State and explain the effect, if any, on n and E_{max} when

(i) the intensity is reduced to $\frac{1}{2}I$ but the wavelength λ is unchanged,

→ $I = \frac{nE}{tA}$, $\frac{I}{2} = (\frac{n}{2})(\text{Constant } \frac{E}{tA})$

So n is reduced to half.

→ $(E_k)_{max}$ remain constant as Energy of photon = constant

(ii) the wavelength λ is reduced but the intensity I is not changed.

→ $I = \frac{nE}{tA} \Rightarrow \text{Constant} = \frac{(n\downarrow)\left(\frac{hc}{\lambda\downarrow}\right)\uparrow}{tA}$

few photons are emitted per unit time ($n\downarrow$)

→ $(E_k)_{max}$ increases as Energy of a photon increases with no change in work function [4]

For Examiner's Use

7 Experiments are conducted to investigate the photoelectric effect.

(a) It is found that, on exposure of a metal surface to light, either electrons are emitted immediately or they are not emitted at all.

Suggest why this observation does not support a wave theory of light.

As per wave theory, electron keep on absorbing energy and will be always be emitted at all frequencies and are emitted continuously.

.... [3]

(b) Data for the wavelength λ of the radiation incident on the metal surface and the maximum kinetic energy E_K of the emitted electrons are shown in Fig. 7.1.

λ/nm	E_K/10^{-19} J
650 240	– 4.44

Fig. 7.1

(i) Without any calculation, suggest why no value is given for E_K for radiation of wavelength 650 nm.

Because 650nm correspond to frequency which is lesser than threshold level of metal. [1]

(ii) Use data from Fig. 7.1 to determine the work function energy of the surface.

E_{photon} = work function + E_K

$$\frac{hc}{\lambda} = \phi_0 + E_K$$

$$\frac{(6.63\times10^{-34})(3.00\times10^{8})}{240\times10^{-9}} = \phi_0 + 4.44\times10^{-19}$$

work function energy = ... J [3]

(c) Radiation of wavelength 240 nm gives rise to a maximum photoelectric current I. The intensity of the incident radiation is maintained constant and the wavelength is now reduced.

For Examiner's Use

State and explain the effect of this change on

(i) the maximum kinetic energy of the photoelectrons,

$\frac{hc}{\lambda} = \phi_0 + (E_K)_{max}$

As $\lambda \downarrow$, so $\uparrow = $ (constant) + Increases

$(E_K)_{max} \uparrow$ [2]

(ii) the maximum photoelectric current I.

$I = \frac{nE}{tA} \Rightarrow I = \frac{n(\frac{hc}{\lambda \downarrow})}{tA}$

$I \downarrow$ as $(\frac{n}{t}) \downarrow$ but $E \uparrow$

[2]

9702/04/M/J/09

8 **(a)** Explain why, for the photoelectric effect, the existence of a threshold frequency and a very short emission time provide evidence for the particulate nature of electromagnetic radiation, as opposed to a wave theory.

→ Wave theory suggests that electrons are emitted for any frequency if exposure time is greater.

→ In particle nature, photons have defined energy dependent upon frequency $E = hf$ and if greater frequency of photons are incident kinetic energy of electrons also increases. [4]

(b) State and explain two relations in which the Planck constant h is the constant of proportionality.

1. $E \propto f$

$E = hf$

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

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

[6] over

Q) If E is the Kinetic energy of a particle, show that De Broglie wavelength of this particle is

$$\lambda = \frac{h}{\sqrt{2mE}}$$

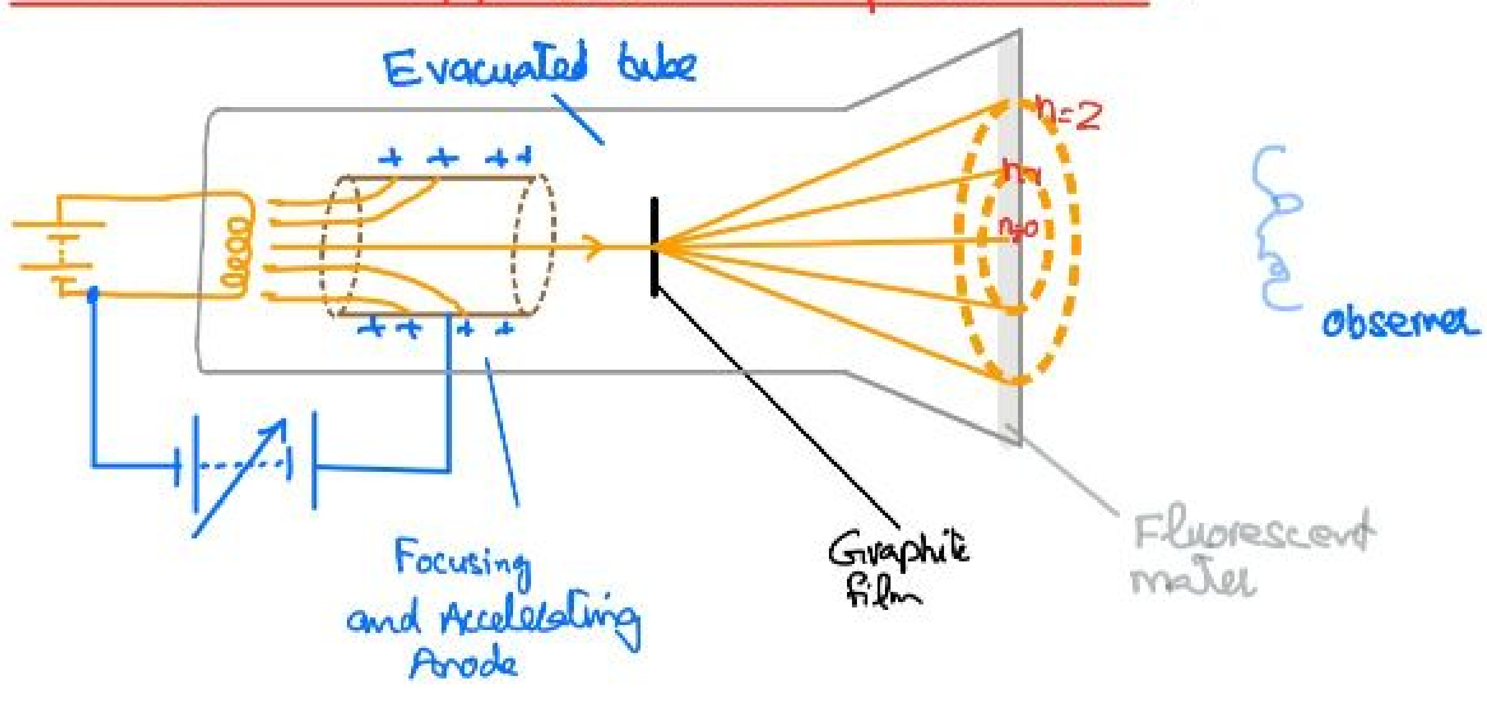
$$E_K = E = \frac{1}{2}mv^2$$

$$v = \sqrt{\frac{2E}{m}}$$

$$\lambda = \frac{h}{p} \Rightarrow \lambda = \frac{h}{mv} \Rightarrow \lambda = \frac{h}{m\sqrt{\frac{2E}{m}}}$$

$$\boxed{\lambda = \frac{h}{\sqrt{2mE}}}$$

Electron- diffraction escperiment :-



Observation:- A fine beam of electrons is incident on a Graphite film. Concentric circular pattern similar to diffraction pattern of monochromatic light through grating wafer is obtained on screen.

22.3 Wave-particle duality

Candidates should be able to:

1 understand that the photoelectric effect provides evidence for a particulate nature of electromagnetic radiation while phenomena such as interference and diffraction provide evidence for a wave nature

2 describe and interpret qualitatively the evidence provided by electron diffraction for the wave nature of particles

3 understand the de Broglie wavelength as the wavelength associated with a moving particle

4 recall and use $\lambda = h / p$

Motion of photon is like a wave

Interaction of photon with matter is like a particle

Louis de Broglie's eq. of wave particle duality:

$$E = hf \quad \text{------(1)}$$

$$E = mc^2 \quad \text{----(2)}$$

$$mc^2 = hf$$

$$mc = h\left(\frac{f}{c}\right)$$

$$p = h\left(\frac{1}{\lambda}\right)$$

$p = mv = mc$

$v = f\lambda$

$c = f\lambda$

$\frac{c}{f} = \lambda$

$\frac{f}{c} = \frac{1}{\lambda}$

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

Momentum defines particle nature

wavelength defines wave nature

Result:- Every particle has an associated wavelength with it.

Smaller the momentum, greater is the wavelength associated with it.

Evidence of wave nature of a particle:

(1) Reflection

(2) Refraction

(3) Diffraction

(4) Interference

Evidence of particle nature of a wave:

(1) Photoelectric effect

Q) Calculate the wavelength associated with an electron which is accelerated through a p.d. of 100V.

First calculate velocity by conservation of energy principle

Gain in K.E = Loss of P.E $\left[V = \frac{W}{Q}\right]$

$$\frac{1}{2}mv^2 = Ve$$

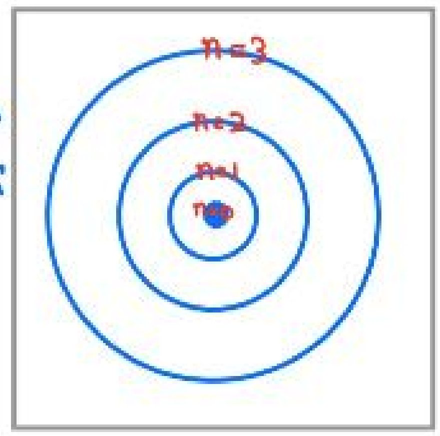
$$v = \sqrt{\frac{2Ve}{m}}$$

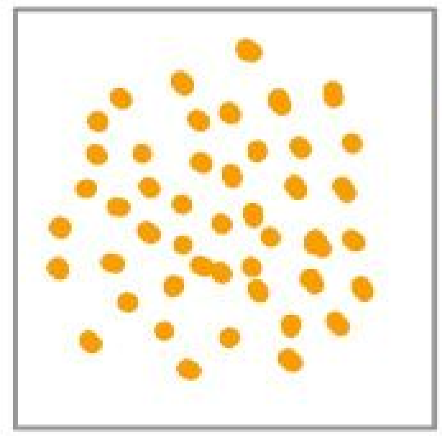
$$v = \sqrt{\frac{2(100)(1.60\times10^{-19})}{9.11\times10^{-31}}} = 3.51\times10^{13}\,ms^{-1}$$

$$\lambda = \frac{h}{mv} = \frac{6.63\times10^{-34}}{(9.11\times10^{-31})(3.51\times10^{13})}$$

$$\lambda = 2.07\times10^{-17}\,m$$

Concentric circular pattern shows diffraction which is the property of a wave.





Distribution of dots shows the particle nature of electron

Reason:- Electron is diffracted through the inter-atomic spacing of Graphite film and further meet to form a concentric circular pattern with multiple orders of diffraction.

Result:- Electron is a particle and diffraction is the property totally associated with a wave. So this experiment provide evidence for wave-nature of a particle.

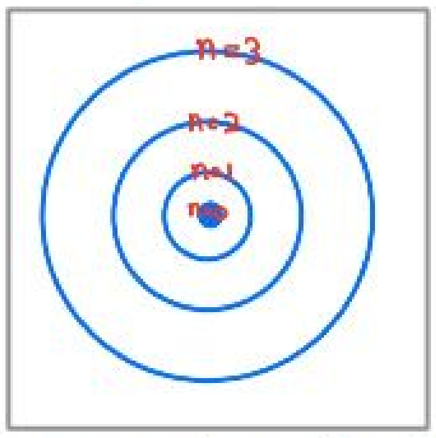
Note:- Radius of concentric circle in diffraction pattern decreases if accelerating voltage is increased because

$$E_k = E_p$$

$$E_k = Ve \Rightarrow E_k \propto (P.d.)$$

But $$\lambda = \frac{h}{\sqrt{2mE_k}}$$

If (P.d.) ↑, (E_k) ↑ and λ ↓. Now λ ↓ and inter-atomic spacing of Graphite film is constant, so lesser is the diffraction and radius of concentric circle for any order of diffraction is decreased.



Diffraction pattern due to low accelerating voltage

Pattern due to high accelerating voltage

Application:-

The best application of wave nature of a particle is electron microscope in which an electron beam is incident on an object to be magnified. These electrons are diffracted through the inter-atomic spacing in the object and its enlarged view is obtained on a screen.

9702/42/M/J/11 /Q 7 (c)

(c) Describe an experiment to demonstrate the wave nature of electrons.
You may draw a diagram if you wish.

....

....

diagram or description showing:

electron beam in a vacuum	B1
incident on thin metal target / carbon film	B1
fluorescent screen	B1
pattern of concentric rings observed	M1
pattern similar to diffraction pattern observed with visible light	A1
	[5]

8 Light of wavelength 590 nm is incident normally on a surface, as illustrated in Fig. 8.1.

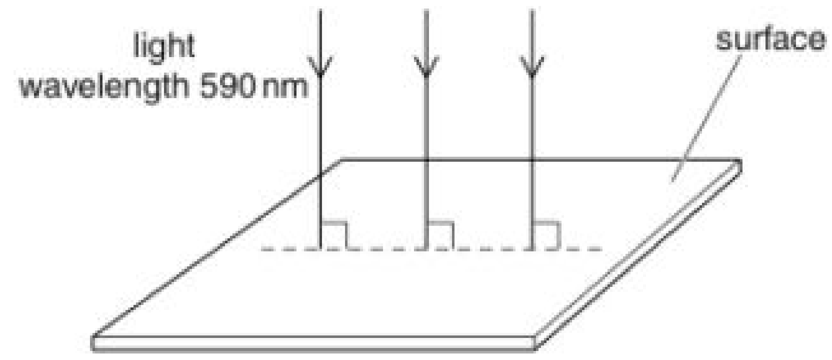


Fig. 8.1

The power of the light is 3.2 mW. The light is completely absorbed by the surface.

(a) Calculate the number of photons incident on the surface in 1.0 s.

$$\text{Power} = \frac{(\text{no. of photons})(\text{Energy of a photon})}{\text{time}} \Rightarrow P = \frac{nE}{t}$$

$$P = \frac{n\left(\frac{hc}{\lambda}\right)}{t} \Rightarrow P = \frac{nhc}{\lambda t}$$

$$3.2\times10^{-3} = \frac{(n)(6.63\times10^{-34})(3.00\times10^{8})}{(590\times10^{-9})(1.0)} \Rightarrow n = 9.49\times10^{15}$$

number = 9.5×10^{15} [3]

(b) Use your answer in **(a)** to determine

(i) the total momentum of the photons arriving at the surface in 1.0 s,

Momentum of a photon: $p = \frac{h}{\lambda} = \frac{6.63\times10^{-34}}{590\times10^{-9}}$

$p = 1.12\times10^{-27}\,\text{Ns}$

Total momentum of n-photons: $P_T = nP$

$P_T = (9.5\times10^{15})(1.12\times10^{-27})$

momentum = 1.06×10^{-11} kg m s^{-1} [3]

(ii) the force exerted on the surface by the light.

$$F = \frac{\Delta P}{\Delta t} = \frac{1.06\times10^{-11}}{1.0}$$

$$= 1.06\times10^{-11}\,\text{N}$$

force = ... N [1]

12 (a) State what is meant by a *photon*.

Discrete packet or quantum of energy of e.m. radiations identified by their frequency by formula E = hf. [2]

(b) A stationary nucleus of samarium-157 ($^{157}_{62}Sm$) emits a gamma-ray (γ-ray) photon of energy 0.57 MeV.

Determine, for one γ-ray photon:

(i) its wavelength

$E = hf$

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

1 eV = 1.60×10^{-19} J

$(0.57)(10^6)(1.60 \times 10^{-19}) = \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{\lambda}$

$\lambda = 2.18 \times 10^{-12}$ m

wavelength = ... m [2]

(ii) its momentum.

By Louis de Broglie relationship

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

$= \frac{6.63 \times 10^{-34}}{2.18 \times 10^{-12}}$

$= 3.04 \times 10^{-22}$

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

$p = \frac{(0.57)(10^6)(1.60 \times 10^{-19})}{3.00 \times 10^8}$

$= 3.04 \times 10^{-22}$ Ns

momentum = ... N s [2]

(c) (i) Using your answer to **(b)(ii)**, determine the speed of the samarium-157 nucleus after emission of the photon.

Mass of Samarium - 157 nucleus = 157 u = $(157)(1.66 \times 10^{-27})$
= 2.61×10^{-25} kg

Initial momentum of system = 0

Final momentum = Momentum of photon + Recoiling momentum of Sm-157
= $3.04 \times 10^{-22} + (-2.61 \times 10^{-25})(v)$

By Principle of conservation of momentum

$0 = 3.04 \times 10^{-22} - 2.61 \times 10^{-25} v$

$v = 1.16 \times 10^{3}$

speed = 1.16×10^{3} m s^{-1} [2]

(ii) By reference to your answer in **(c)(i)**, explain quantitatively why the speed of the samarium-157 nucleus may be assumed to be negligible compared with the speed of the photon.

Speed of Photon = 3.00×10^{8} m s^{-1} and speed of Sm-157 nucleus is 1.16×10^{3} m s^{-1}. Since 1.16×10^{3} is much lesser than 3.00×10^{8} and can be neglected. [1]

[Total: 9]

22.4	Energy levels in atoms and line spectra

Candidates should be able to:

1 understand that there are discrete electron energy levels in isolated atoms (e.g. atomic hydrogen)

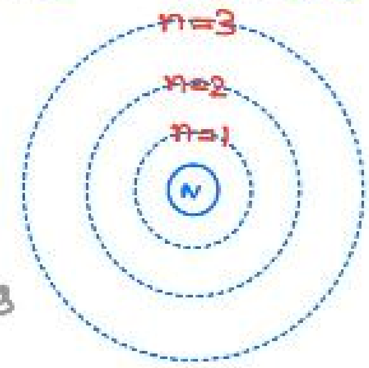
2 understand the appearance and formation of emission and absorption line spectra

3 recall and use $hf = E_1 - E_2$

Assumptions of Hydrogen atom:-

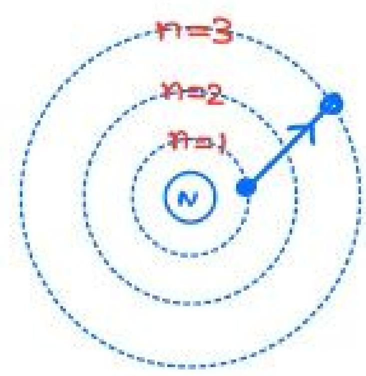
1- Electrons can revolve around the nucleus in discrete orbits / energy level.

Electron can not complete at 2π rad rotation around nucleus in the space b/w two orbits or in the space b/w a nucleus and its first orbit.



2- Electron does not radiate any energy if revolving in its own orbit/ energy level.

3- When an electron absorbs <u>sufficient</u> amount of energy then it moves to higher orbit/ energy level (away from nucleus) and the atom is said to be excited.



4- During de-excitation, electron jumps from higher energy level to lower energy level/orbit and releases energy in the form of photons.

$$E_n - E_p = E_{Photon}$$

$$E_n - E_p = \frac{hc}{\lambda}$$

Here, E_n - Energy of an electron in higher (n^{th}) energy level.

E_p - Energy of an electron in lower (p^{th}) energy level)

Q) How do you know that electrons have definite energy values in discrete orbits?

Photon of definite wavelength is released during de-excitation process. This emitted wavelength depends upon the energy of electron in its initially higher energy and finally lower energy level.

$$E_n - E_p = \frac{hc}{\lambda}$$

Hence, energy of an electron in discrete orbits is also defined.

HYDROGEN SPECTRA:-

Energy of an electron in n^{th} orbit/ energy level is

$$E_n = -\frac{13.6}{n^2} \text{ eV}$$

For first orbit/energy level, $n = 1$

$$E_1 = -\frac{13.6}{1^2} = -13.6 eV$$

For 2^{nd} orbit/energy level, $n = 2$

$$E_2 = -\frac{13.6}{2^2} = -3.4 eV$$

For 3^{rd} orbit/energy level, $n = 3$

$$E_3 = -\frac{13.6}{3^2} = -1.5 eV$$

For 4^{th} orbit/energy level, $n = 4$

$$E_4 = -\frac{13.6}{4^2} = -0.85 eV$$

⋮

For infinite orbit/energy level, $n = \infty$

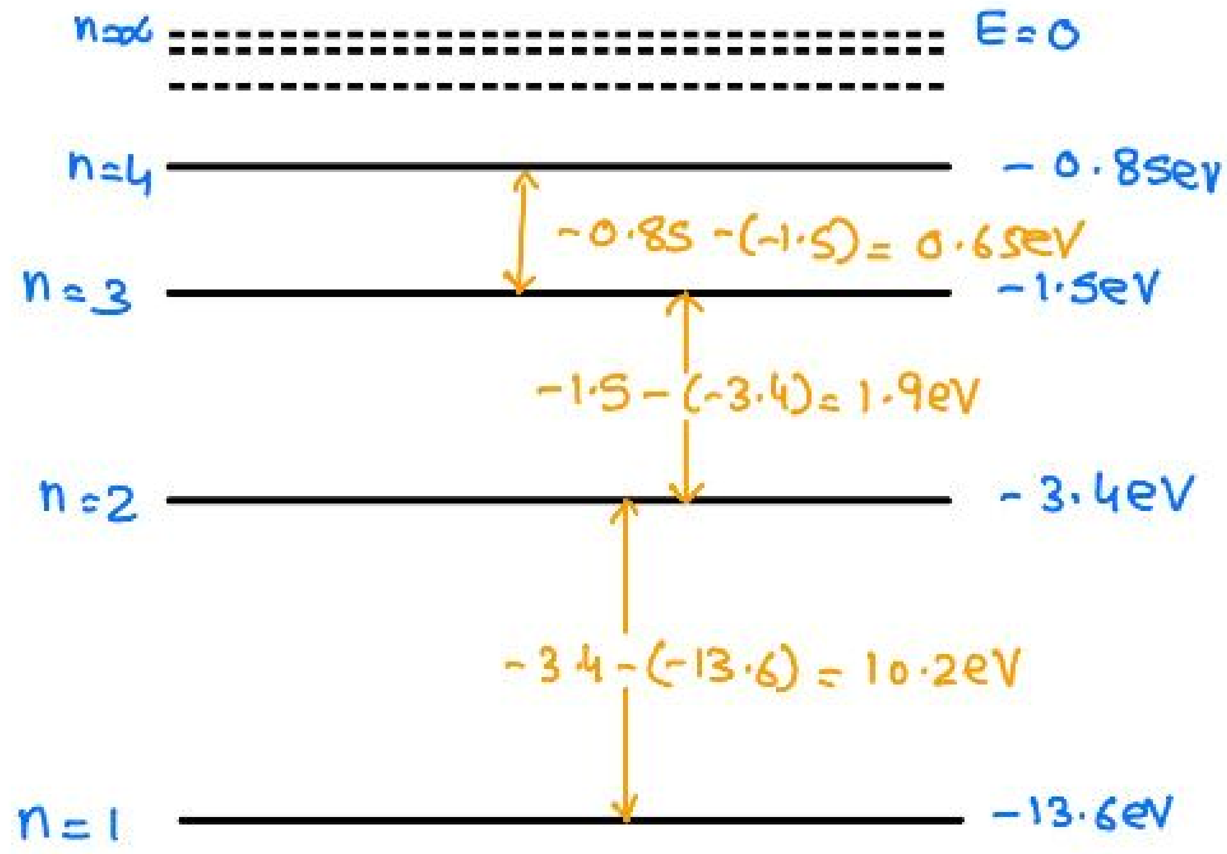
$$E_\infty = -\frac{13.6}{\infty^2} = 0$$

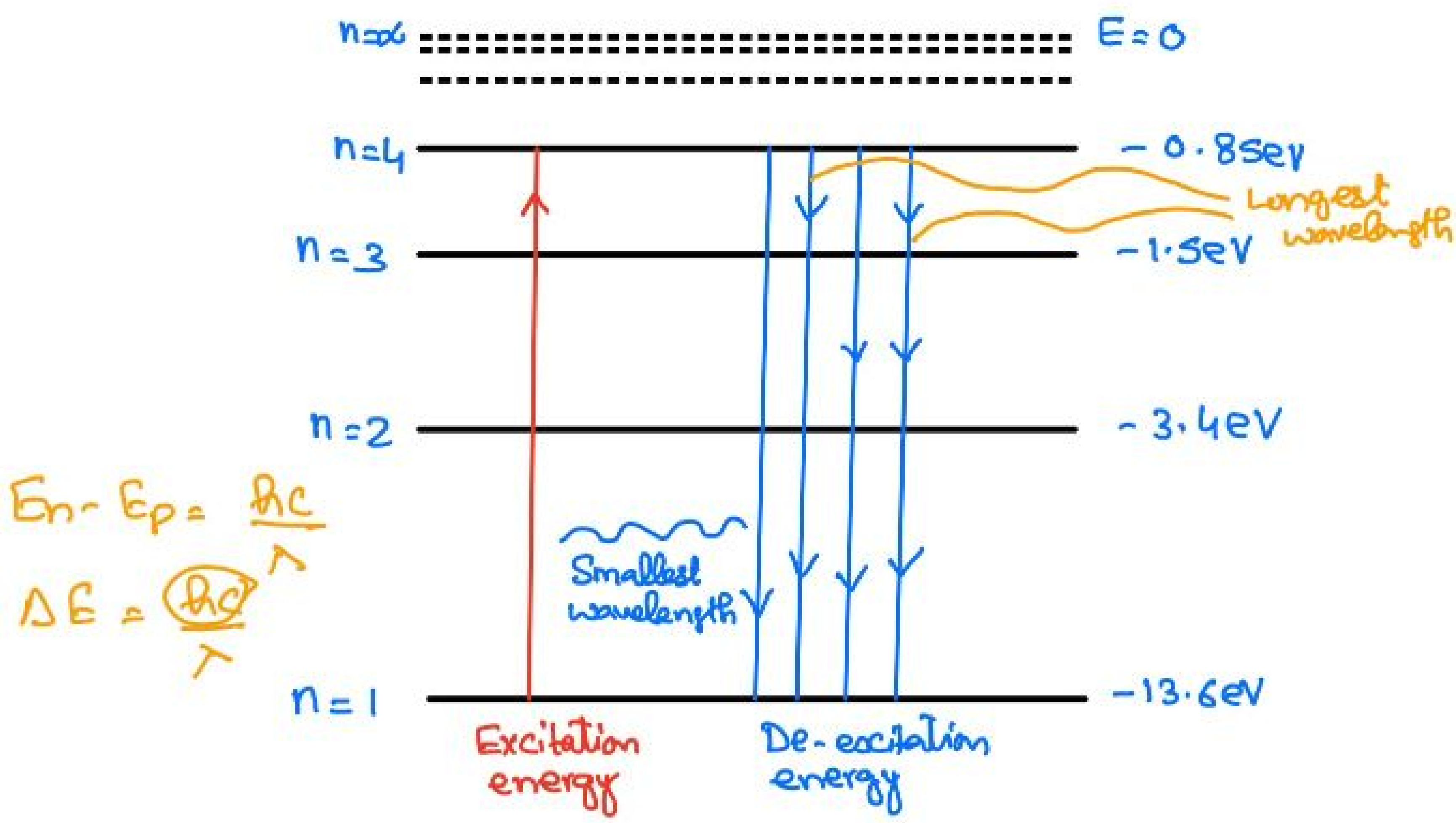
Significance of -ve sign:- All energy levels represent the -ve energy of an electron because of

(i) Attractive force between the +ve nucleus and the -vely charged electron.

(ii) Maximum energy of an electron outside an atom is zero and this energy reduces from zero and becomes in -ve if an electron comes closer to nucleus.

Energy Level diagram:-





Note:

1- When an electron absorb sufficient amount

of energy i.e. $[-0.85-(-13.6)] = 12.75\text{ eV}$
$= 12.75 \times 1.60 \times 10^{-19} = 2.04 \times 10^{-18}\text{ eV}$ then it moves from $n=1$ to $n=4$ in one step as shown in the diagram (Red arrow) and the atom is said to be excited.

2 - During de-excitation, electron may go back to its ground state in one step or in a series of steps given as (by blue lines)

$n=4 \longrightarrow n=3 \longrightarrow n=1$

$n=4 \longrightarrow n=2 \longrightarrow n=1$

$n=4 \longrightarrow n=3 \longrightarrow n=2 \longrightarrow n=1$

3 - When an electron jumps from $n=4$ to $n=1$ in one step, then the wavelength of emitted photon is given as

$$E_4 - E_1 = \frac{hc}{\lambda}$$

$$[-0.85-(-13.6)][1.60 \times 10^{-19}] = \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{\lambda}$$

$$\lambda = 9.76 \times 10^{-8}\text{ m}$$
$$= 97.6\text{ nm}$$

The emitted photons lie in the UV region of e.m. spectrum.

4- Each line (Horizontal here) represents the specific energy of an electron. The gap b/w two energy levels represents the difference of energy which electrons needed to make transition.

Greater is the gap between n = 1 and n=2 because of greater difference of energy of electrons in these adjacent orbits / levels.

5- Each arrow (vertical arrow directed downward here) corresponds to a specific photon energy released when an electron changes its energy level. Since energy change is discrete, so this leads to the excistance of discrete of discrete electron energy levels in an atom.

7 **(a)** The emission spectrum of atomic hydrogen consists of a number of discrete wavelengths. Explain how this observation leads to an understanding that there are discrete electron energy levels in atoms.

$E_n - E_p = \frac{hc}{\lambda}$

Each emitted wavelength results from transition of electron between its initial and final energy levels. So discrete energy change signifies descrete energy levels. [2]

(b) Some electron energy levels in atomic hydrogen are illustrated in Fig. 7.1.

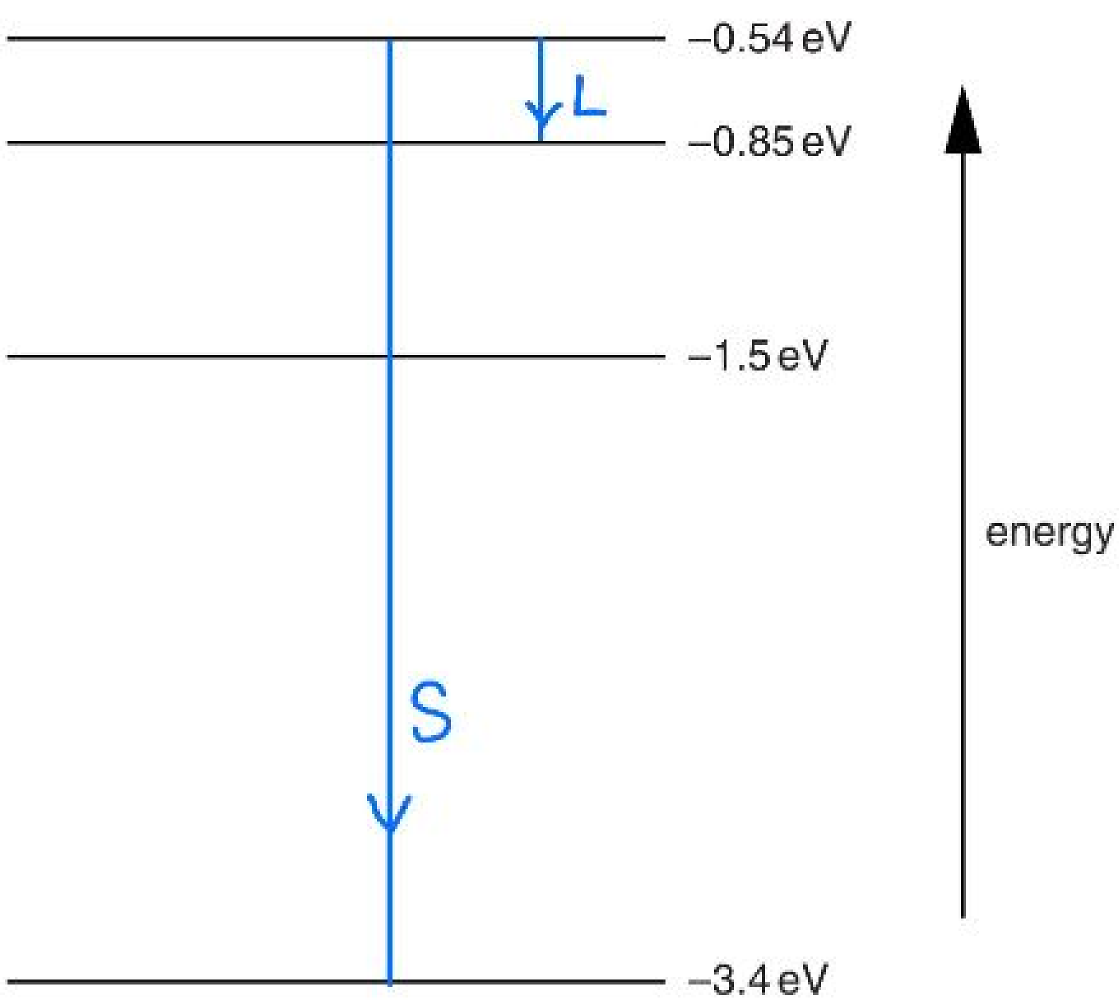


Fig. 7.1

The longest wavelength produced as a result of electron transitions between two of the energy levels shown in Fig. 7.1 is 4.0×10^{-6} m.

Least

$\Delta E = \frac{hc}{\lambda} \Rightarrow \Delta E \propto \frac{1}{\lambda_{Longest}}$

For Examiner's Use

(i) On Fig. 7.1,

1. draw, and mark with the letter L, the transition giving rise to the wavelength of 4.0×10^{-6} m, [1]

2. draw, and mark with the letter S, the transition giving rise to the shortest wavelength. [1]

$\Delta E_{greatest} \propto \frac{1}{\lambda_{Least}}$

(ii) Calculate the wavelength for the transition you have shown in **(i) part 2**.

$E_n - E_p = \frac{hc}{\lambda}$

$[-0.54 - (-3.4)][1.60\times10^{-19}] = \frac{(6.63\times10^{-34})(3.00\times10^{8})}{\lambda}$

$\lambda = 4.35 \times 10^{-7}$ m

wavelength = 4.35×10^{-7} m m [3]

(c) Photon energies in the visible spectrum vary between approximately 3.66 eV and 1.83 eV.

Determine the energies, in eV, of photons in the visible spectrum that are produced by transitions between the energy levels shown in Fig. 7.1.

Transition b/w −0.54eV to −3.4eV = −0.54−(−3.4) = 2.86eV ✓

Transition b/w −0.85eV to −3.4eV = −0.85−(−3.4) = 2.55eV ✓

Transition b/w −1.5eV to −3.4eV = −1.5−(−3.4) = 1.9eV ✗

photon energies 2.86 and 2.55 eV [2]

For Examiner's Use

7 (a) State an effect, one in each case, that provides evidence for

(i) the wave nature of a particle,

Electron diffraction experiment ....[1]

(ii) the particulate nature of electromagnetic radiation.

Photoelectric effect ....[1]

(b) Four electron energy levels in an atom are shown in Fig. 7.1.

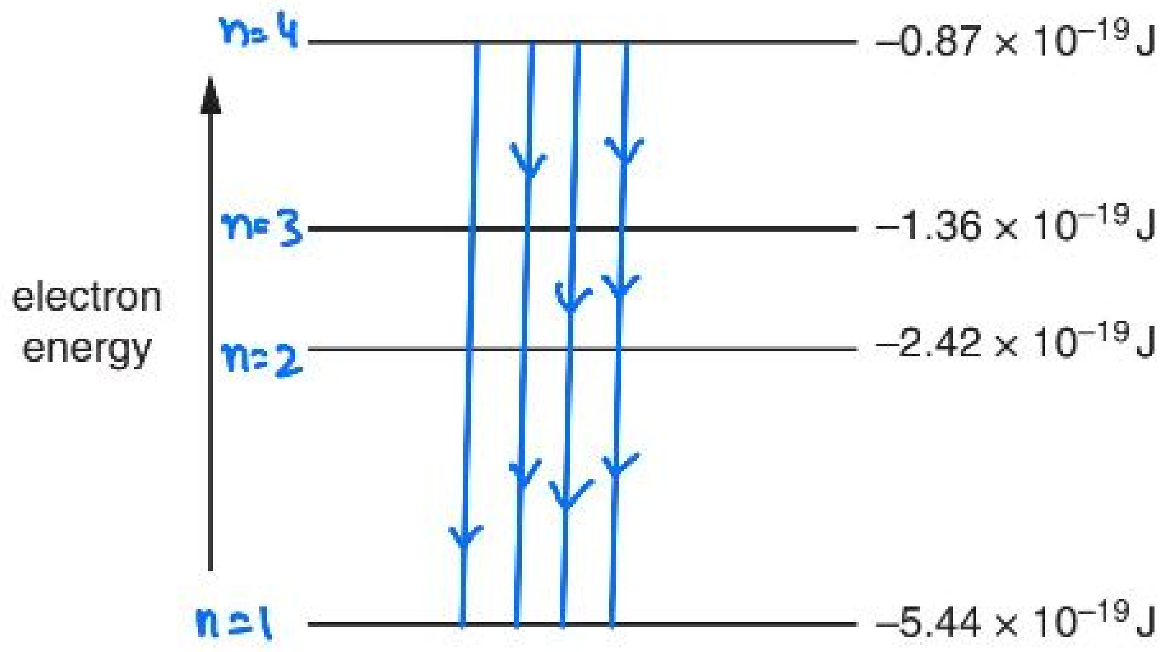


Fig. 7.1 (not to scale)

An emission spectrum is associated with the electron transitions between these energy levels.
For this spectrum,

n = 4 ① → n=1
n = 4 ② → n=3 ③ → n=1
n = 4 ④ → n=2 ⑤ → n=1
n = 4 → n=3 ⑥ → n=2 → n=1

(i) state the number of lines,

6 ....[1]

(ii) calculate the minimum wavelength.

Minimum wavelength corresponds to greatest difference of energy of electrons

$$E_n - E_p = \frac{hc}{\lambda}$$

$$[-0.87-(-5.44)]10^{-19}[1.60\times10^{-19}] = \frac{(6.63\times10^{-34})(3.00\times10^{8})}{\lambda}$$

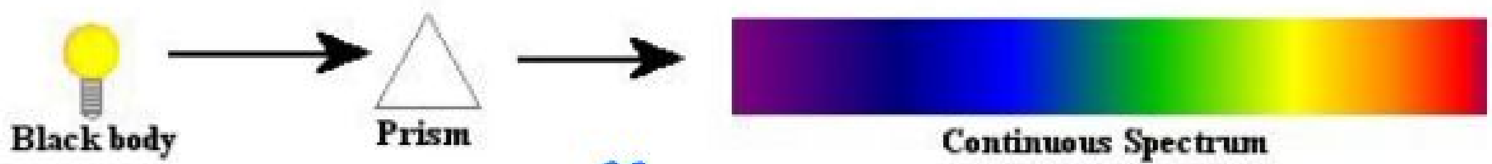
λ = ______

wavelength = ... m [2]

CONTINUOUS AND LINE SPECTRA:-

(a) Continuous spectra:-

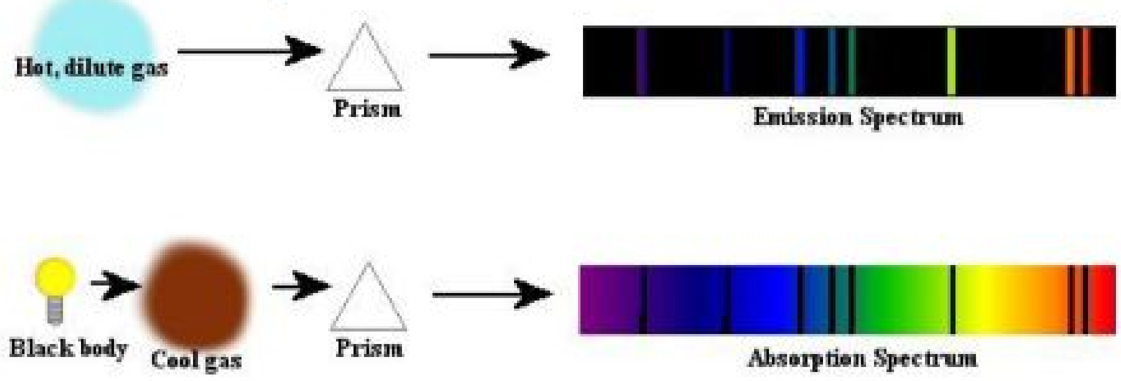
Defined sequence of colours obtained as white light passes through a prism with no observable gaps between colours. It contains all the wavelengths or colours such as in Rainbow.



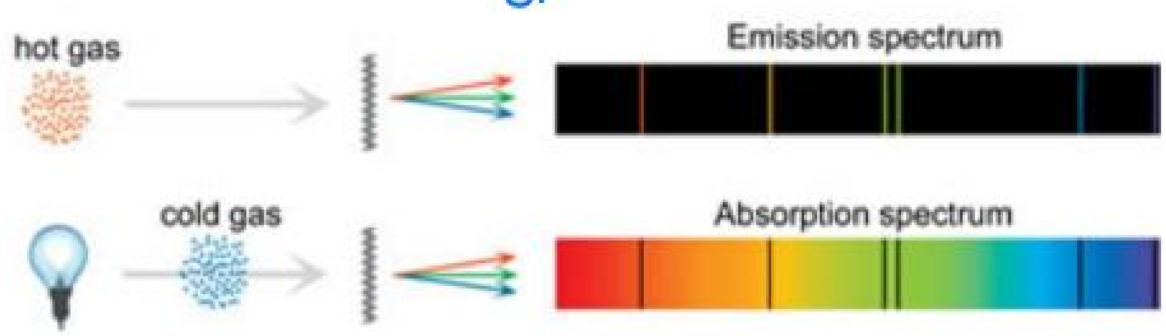
or

(b) Line spectra:-

The spectrum with huge gaps between lines and contains only a few wavelengths. Line spectrum is either an absorption spectrum or an emission spectrum.



or



(i) The Emission Line Spectra:-

Identification:- It consists of a series of separate bright lines of definite wavelength (colour) separated by dark regions.

Production:- It is produced by the electron transitions within individual atoms of vapours or gases at low pressure, as electrons jump from higher to lower energy levels within an atom.

Examples:-

1- Series of lines obtained from filament lamp containing Neon gas.
2- Light emitted when a high p.d. is applied across a discharge tube containing a gas at low pressure.

Use:- Since the wavelengths of the lines are characteristics of the element emitting the light. Therefore, Emission line spectra is used to identify elements.

(ii) The Absorption Line spectra:-

Identification:- It looks a continuous spectrum crossed by dark lines due to some missing frequencies.

Production:- When white light passes through a gas, some electrons absorb energy and move to higher energy levels. When these electrons return to lower levels, photons are emitted in all directions, rather than in the original direction of white light. Therefore, this accounts for the relatively lower intensity of the various frequencies and the missing lines of the continuous spectrum.

11 A beam of light consists of a continuous range of wavelengths from 420 nm to 740 nm.
The light passes through a cloud of cool gas, as shown in Fig. 11.1.

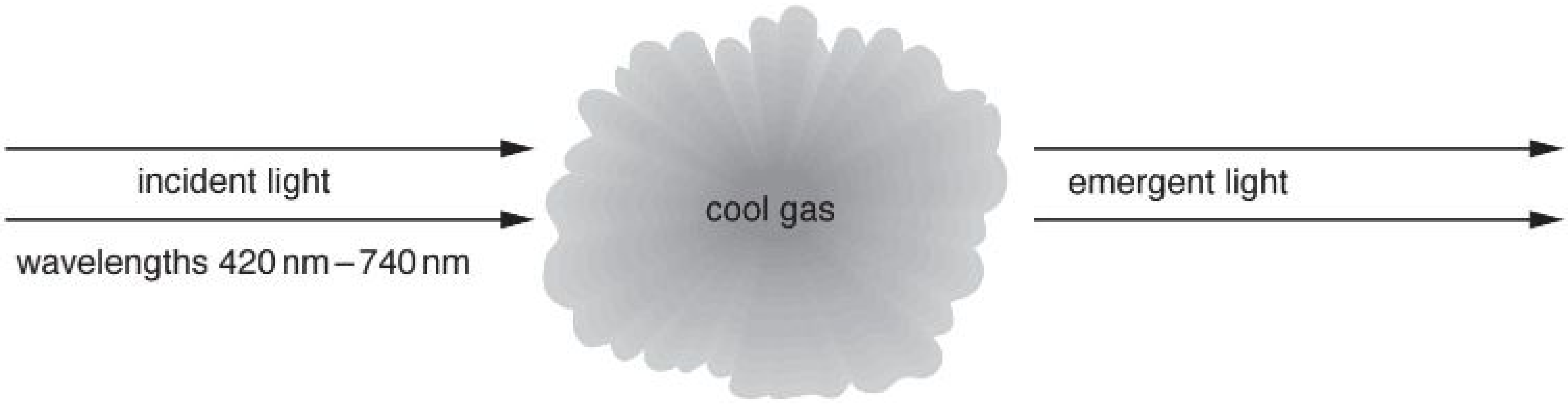


Fig. 11.1

(a) The spectrum of the light emerging from the cloud of cool gas is viewed using a diffraction grating.
Explain why this spectrum contains a number of dark lines.

electrons (in gas atoms/molecules) interact with photons

photon energy causes electron to move to higher energy level/to be excited

photon energy = difference in energy of (electron) energy levels

when electrons de-excite, photons emitted in all directions (so dark line)

[4]

(b) Some of the electron energy levels of the atoms in the cloud of gas are represented in Fig. 11.2.

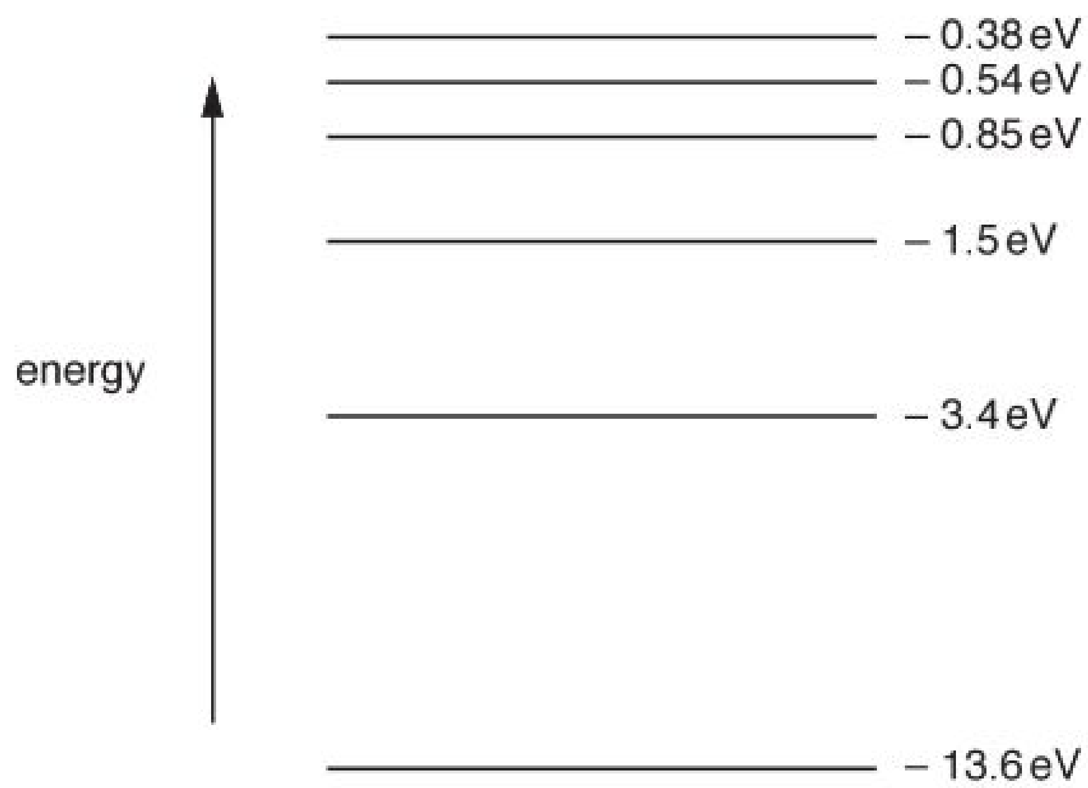


Fig. 11.2 (not to scale)

(i) Light of wavelength 420 nm has a photon energy of 2.96 eV.
Calculate the photon energy, in eV, of light of wavelength 740 nm.

photon energy $\propto 1 / \lambda$

energy = 1.68 eV

or

$E = hc / \lambda$

$E = 6.63 \times 10^{-34} \times 3.0 \times 10^{8} / (740 \times 10^{-9})$

$= 2.688 \times 10^{-19}$ J

energy = 1.68 eV

photon energy = ... eV [2]

(ii) Use data from **(i)** and your answer in **(i)** to show, on Fig. 11.2, the changes in energy levels giving rise to the dark lines in **(a)**. [2]

[Total: 8]

3.4 eV → 1.5 eV
3.4 eV → 0.85 eV
3.4 eV → 0.54 eV
all correct and none incorrect 2/2
2 correct and 1 incorrect or only 2 correctly drawn 1/2