PROSPERITY ACADEMY

A2 PHYSICS 9702

Crash Course

RUHAB IQBAL

QUANTUM PHYSICS

COMPLETE NOTES

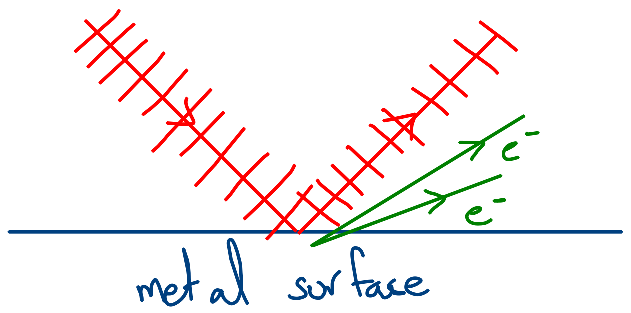
0331 - 2863334

ruhab.prosperityacademics@gmail.com

Quantum Physics:-

In AS, we studied waves transfer energy from one point to another.

In AS, you understood light waves.
- diffraction
- interference



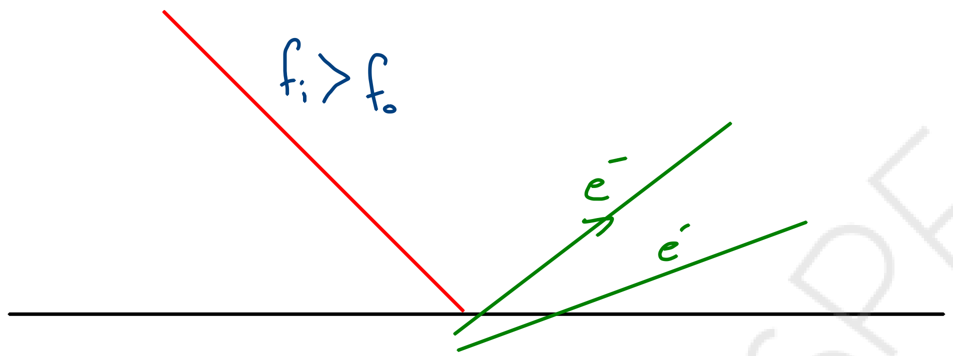
this didn't happen at all

If light is wave-like:-

- electrons must be emitted from the surface of a metal if light is incident for a sufficiently long enough time
- electrons must be emitted continuously and randomly
- this must happen at any frequency (given intensity is constant)
- When intensity is increased, then the energy of the electrons must increase

$$\uparrow I = \frac{P}{A} = \frac{E\uparrow}{At}$$

In reality, photoelectric effect occurs:-



f_i : incident frequency

f_0 : threshold frequency

Photoelectric effect:- When light of a frequency above the threshold frequency is incident on a target metal, electrons are emitted from its surface

- Emission of electrons happens at only a higher frequency than the threshold frequency.
- electrons are emitted spontaneously (no time required) when $f_i > f_0$
- increasing the intensity, didnot increase the $E_{K\,max}$ of electrons instead the rate of ejection increased
- increasing the frequency decreases the rate of ejection and increases the $E_{K\,max}$ of electrons.

$c = f\lambda$

$f = \dfrac{c}{\lambda}$ → const

$f \propto \dfrac{1}{\lambda}$

Threshold frequency:- It is the minimum frequency for photons incident on a target metal above which electrons are emitted from the metal.

Threshold wavelength:- It is the maximum wavelength for photons incident on a target metal below which electrons are emitted.

Photons:- It is the smallest indivisible ~~packet of energy~~ of electromagnetic radiation.
quantum of energy

Einstein's Pointers:-

1) Energy of a single photon is directly proportional to it's frequency.

$E \propto f$

Energy of n photons = nhf

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

$\hookrightarrow$ Planck's constant

$E_T = nhf$

2) Photoelectric effect only occurs for $f_i > f_o$

3) The maximum kinetic energy of the ejected electron is proportional to the difference between the incident and threshold frequency.

$E_{K_{max}} \propto (f_i - f_o)$

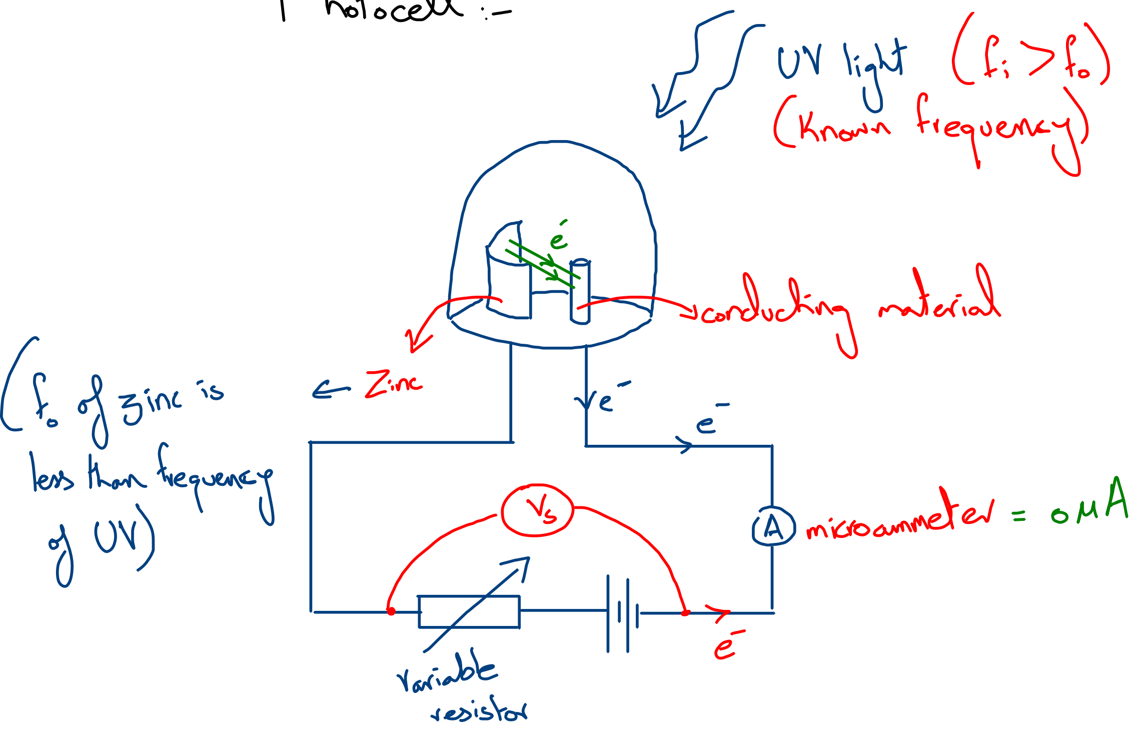
$E_{K_{max}} = h(f_i - f_o) \Rightarrow E_{K_{max}} = hf_i - hf_o$

or

$E_{K_{max}} = \frac{hc}{\lambda_i} - \frac{hc}{\lambda_o}$

$hf_o = \phi$: Work function of the metal:- Minimum amount of incident photon energy required for the photoelectric effect to occur.

Photocell :-



Stopping Voltage (V_s) :- It is the voltage at which an electron from the photocell with the highest Kinetic energy is completely stopped.

$$V = \frac{W}{q} \Rightarrow W = Vq \Rightarrow E_{K\,max} = V_s \times e$$

$$E_{K\,max} = hf_i - hf_o$$

$$eV_s = hf_i - hf_o \Rightarrow V_s = \underbrace{\frac{h}{e}}_{const} f_i - \underbrace{\frac{h}{e}}_{const} f_o$$

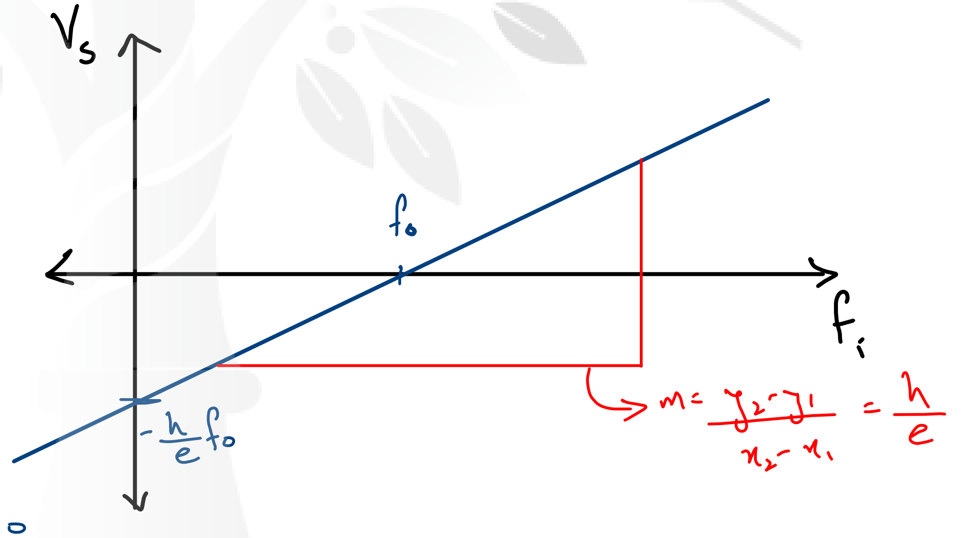
$$y = m\,x + c$$

if $V_s = 0$

$$0 = \frac{h}{e} f_i - \frac{h}{e} f_o$$

$$\cancel{\frac{h}{e}} f_o = \cancel{\frac{h}{e}} f_i$$

$$f_i = f_o$$



1) Einstein was proved right
2) Planck's constant was found ($m = \frac{h}{e}$)
3) threshold frequency could be deduced very accurately.

Q) Prove that increasing intensity will increase the rate of ejection of electrons:-

$$I = \frac{P}{A} = \frac{E}{t \times A} \xrightarrow[\text{particulate theory}]{\text{using Einstein's}} = \frac{nhf}{tA} \Rightarrow \uparrow I = \uparrow \frac{n}{t} \times \underbrace{\frac{hf}{A}}_{\text{const}}$$

Q) Show what happens when frequency is increased keeping intensity constant.

$$I = \frac{nhf}{tA} \Rightarrow \underbrace{\frac{IA}{h}}_{\text{const}} \times \frac{1}{f\uparrow} = \frac{n}{t}\downarrow \qquad \frac{1}{f\uparrow} \propto \frac{n}{t}\downarrow$$

1) Increasing frequency, Decreases rate of ejection.

2) $\uparrow E = hf\uparrow \Rightarrow$ Increasing frequency must also increase energy of electrons

Light has wave - particle duality :-

Energy of a photon :-

1) $E = hf$ or $E = \frac{hc}{\lambda}$

2) $m = \frac{E}{c^2} \Rightarrow E = mc^2$

mass is the property of a material that has energy

* $\frac{E}{c} = mc$

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

De Broglie's wavelength :-

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

2) $\frac{E}{c} = p \Rightarrow E = pc$

$$p\cancel{c} = \frac{h\cancel{c}}{\lambda} \Rightarrow \boxed{p = \frac{h}{\lambda}}$$

Anything that has momentum must have a wavelength.

$\uparrow p \propto \frac{1}{\lambda \downarrow}$

(bigger mass -> bigger momentum)

$\downarrow p \propto \frac{1}{\lambda \uparrow}$

(smaller mass -> smaller momentum)

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.

Wave theory predicts electrons will always be emitted if light of any frequency is exposed on a metal surface for a sufficiently long enough time.

[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

$f_i > f_o$

$\lambda_i < \lambda_o$

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

Most probably 650 nm is greater than the threshold wavelength.

[1]

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

$$E_{K max} = \frac{hc}{\lambda_i} - \frac{hc}{\lambda_o} \rightarrow \phi$$

$$\phi = \frac{(6.63\times10^{-34})(3\times10^{8})}{240\times10^{-9}} - 4.44\times10^{-19}$$

$$\phi = 3.84\times10^{-19}$$

work function energy = 3.8×10^{-19} 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.

State and explain the effect of this change on

(i) the maximum kinetic energy of the photoelectrons,

It will increase as the energy of the incident photons has increased ($\uparrow E \propto \frac{1}{\lambda\downarrow}$)

[2]

$$E = \frac{hc}{\lambda} \quad \text{const}$$

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

(ii) the maximum photoelectric current I.

The current will reduce as the number of incident photons per unit time has decreased

[2]

$$I = \frac{E}{A\times t} \Rightarrow I = \frac{nhf}{t\times A}$$

$$\frac{IA}{h} \times \frac{\lambda}{c} = \frac{n}{t}$$

const

$$\downarrow\lambda \propto \frac{n}{t}\downarrow$$

7 An explanation of the photoelectric effect includes the terms photon energy and work function energy.

For Examiner's Use

(a) Explain what is meant by

(i) a *photon*,

It is the smallest indivisible quantum of energy of electromagnetic radiation.

[2]

(ii) *work function energy*.

Minimum incident photon energy required to eject an electron from a target metal.

[1]

(b) In an experiment to investigate the photoelectric effect, a student measures the wavelength λ of the light incident on a metal surface and the maximum kinetic energy E_{max} of the emitted electrons. The variation with E_{max} of $\frac{1}{\lambda}$ is shown in Fig. 7.1.

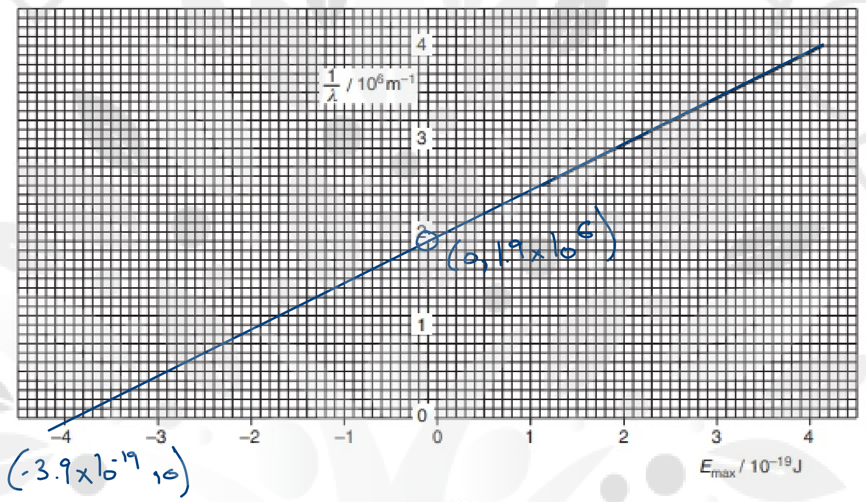


Fig. 7.1

(i) The work function energy of the metal surface is Φ.
State an equation, in terms of λ, Φ and E_{max}, to represent conservation of energy for the photoelectric effect. Explain any other symbols you use.

$E_{max} = \frac{hc}{\lambda} - \phi$

h: Planck's constant   c: speed of light in vacuum [2]

(ii) Use your answer in **(i)** and Fig. 7.1 to determine

1. the work function energy Φ of the metal surface,

at $\frac{1}{\lambda} = 0$, $E_{max} = -\phi$

$+3.9\times10^{-19} = +\phi$

Φ = 3.9×10^{-19} J [2]

2. a value for the Planck constant.

$m = \frac{1}{hc} \Rightarrow \frac{1.9\times10^{6} - 0}{0 - (-3.9\times10^{-19})}$

$\frac{3.9\times10^{-19}}{1.9\times10^{6}\times3\times10^{8}} = h = 6.84\times10^{-34}$

Planck constant = 6.8×10^{-34} Js [3]

$E_{max} = \frac{hc}{\lambda_i} - \frac{hc}{\lambda_o}$

$E_{max} = hc\left(\frac{1}{\lambda_i} - \frac{1}{\lambda_o}\right)$

$\frac{E_{max}}{hc} = \frac{1}{\lambda_i} - \frac{1}{\lambda_o}$

$\frac{1}{\lambda_i} = \frac{1}{hc}(E_{max}) + \frac{1}{\lambda_o}$

$y = m \quad x + c$

x int:-

$0 = \frac{1}{hc}E_{max} + \frac{1}{\lambda_o}$

$-\frac{hc}{\lambda_o} = E_{max}$

$-\phi = E_{max}$

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

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

(a)

~~(i) State what is meant by threshold frequency.~~

(ii) Calculate threshold frequency for platinum.

$\phi = hf_0 \Rightarrow (6.63 \times 10^{-34}) f_0 = 9 \times 10^{-19}$

$f_0 = 1.4 \times 10^{15} \Rightarrow 14 \times 10^{14}$

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

$f = \frac{c}{\lambda} \Rightarrow \frac{3 \times 10^8}{300 \times 10^{-9}} - \frac{3 \times 10^8}{600 \times 10^{-9}} \Rightarrow \overset{f}{(10 \times 10^{14} - 5 \times 10^{14})}$

sodium & zinc will give photoelectric effect

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

$I = \frac{E}{At} \Rightarrow I = \frac{n}{t} \times \frac{hf}{A}$

$\frac{AI}{h} \times \frac{1}{f\uparrow} = \frac{n}{t}\downarrow$

rate of ejection decreases

9 For a particular metal surface, it is observed that there is a minimum frequency of light below which photoelectric emission does not occur. This observation provides evidence for a particulate nature of electromagnetic radiation.

(a) State three further observations from photoelectric emission that provide evidence for a particulate nature of electromagnetic radiation.

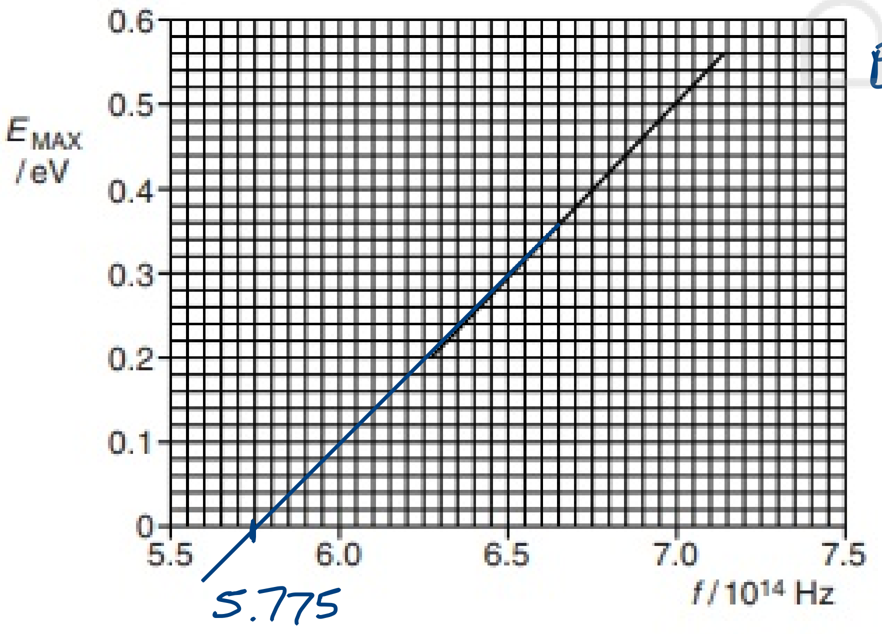
1. Electrons are emitted spontaneously/instantly (no time required)

2. Increasing the frequency increases the energy of the electrons

3. Rate of emission is proportional to intensity

[3]

(b) Some data for the variation with frequency f of the maximum kinetic energy E_{MAX} of electrons emitted from a metal surface are shown in Fig. 9.1.



$E_{max} = hf_i - \underbrace{hf_0}$

$y = mx + c$

$0 = hf_i - hf_0$

$\cancel{h}f_0 = \cancel{h}f_i$

$f_i = f_0$

Fig. 9.1

(i) Explain why emitted electrons may have kinetic energy less than the maximum at any particular frequency.

maybe the photon-electron interaction happens below the surface so energy is required to bring the electron to the surface. [2]

(ii) Use Fig. 9.1 to determine

1. the threshold frequency,

threshold frequency = 5.8×10^{14} Hz [1]

2. the work function energy, in eV, of the metal surface.

$\phi = hf_0$

$(6.63\times10^{-34})(5.8\times10^{14}) = 3.84\times10^{-19}$ J

1.6×10^{-19} J $=$ 1 eV

$3.84\times10^{-19} = x$ eV $\Rightarrow x = 2.4$

work function energy = 2.4 eV [3]

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

....

....

.... [2]

(b) A beam of light is incident normally on a metal surface, as illustrated in Fig. 8.1.

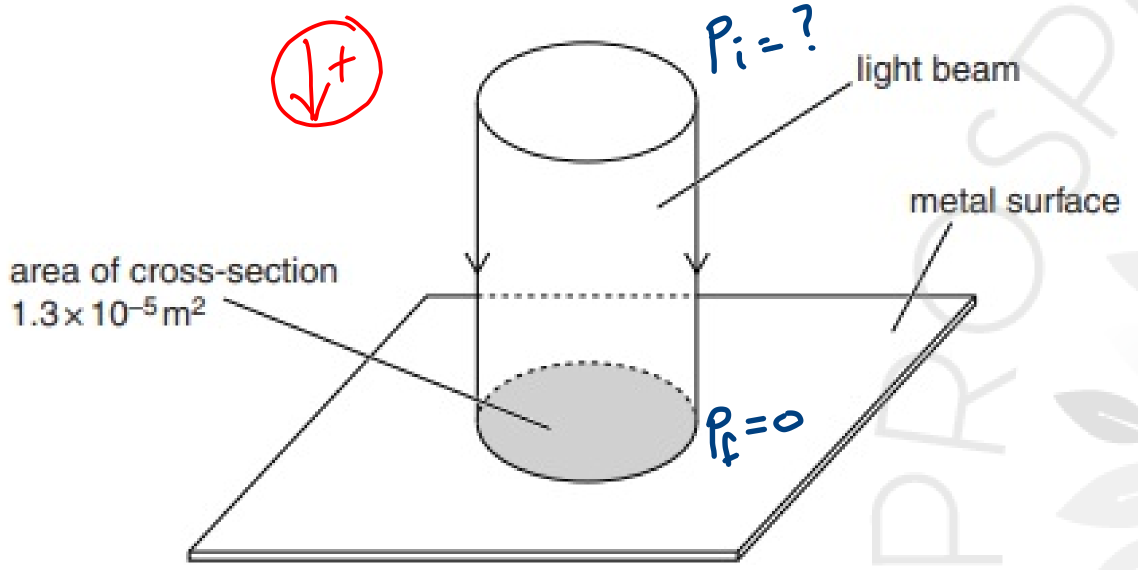


Fig. 8.1

The beam of light has cross-sectional area $1.3 \times 10^{-5}\,m^2$ and power $2.7 \times 10^{-3}\,W$.
The light has wavelength 570 nm.

The light energy is absorbed by the metal and no light is reflected.

(i) Show that a photon of this light has an energy of $3.5 \times 10^{-19}\,J$.

$$E = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{(570 \times 10^{-9})} = 3.49 \times 10^{-19}$$

$$\simeq 3.5 \times 10^{-19}\,J$$

[1]

(ii) Calculate, for a time of 1.0 s,

1. the number of photons incident on the surface,

$$I = \frac{P}{A}$$

$$I = \frac{2.7 \times 10^{-3}}{1.5 \times 10^{-5}}$$

Alt:-

$$P = \frac{E}{t} \Rightarrow P = \frac{nE}{t}$$

$$n = \frac{P \times t}{E}$$

$$I = \frac{E}{A t} = \frac{n \times \frac{hc}{\lambda}}{A t}$$

$$\frac{2.7 \times 10^{-3}}{\cancel{1.5 \times 10^{-5}}} = \frac{n\,(3.5 \times 10^{-19})}{\cancel{1.5 \times 10^{-5}} \times 1} \Rightarrow n = \frac{2.7 \times 10^{-3}}{3.5 \times 10^{-19}}$$

number = 7.7×10^{15} [2]

2. the change in momentum of the photons.

$$\Delta p = P_f - P_i \Rightarrow 0 - P_i = \Delta p$$

$$P_i = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{570 \times 10^{-9}} = -1.16 \times 10^{-27} = \Delta p$$

$$\Delta p_n = 7.7 \times 10^{15} \times 1.16 \times 10^{-27} = 8.96 \times 10^{-12}$$

change in momentum = 9.0×10^{-12} kg m s^{-1} [3]

(c) Use your answer in **(b)(ii)** to calculate the pressure that the light exerts on the metal surface.

$$P = \frac{F}{A} = \frac{\Delta p}{\Delta t \times A} = \frac{9 \times 10^{-12}}{1 \times 1.3 \times 10^{-5}} = 6.923 \times 10^{-7}$$

pressure = 6.9×10^{-7} Pa [2]

8 A photon of wavelength 6.50×10^{-12} m is incident on an isolated stationary electron, as illustrated in Fig. 8.1.

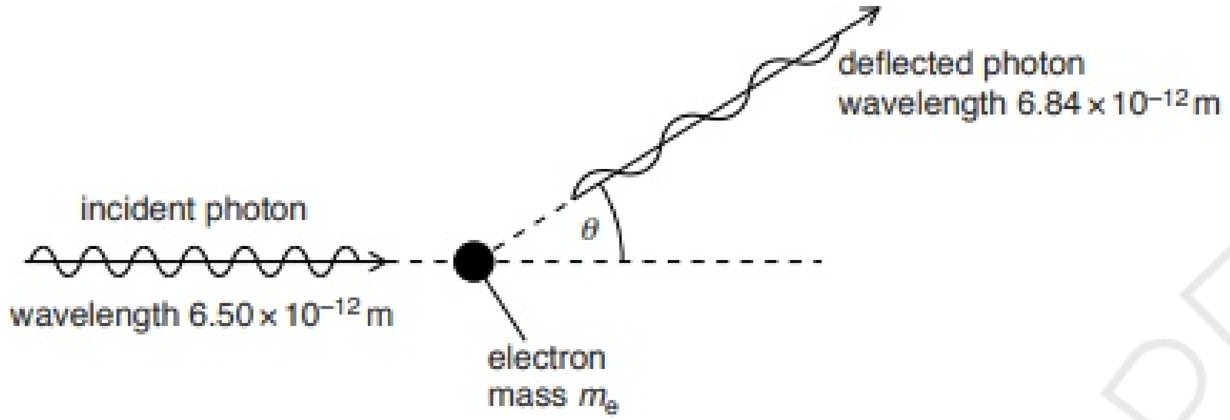


Fig. 8.1

The photon is deflected elastically by the electron of mass m_e. The wavelength of the deflected photon is 6.84×10^{-12} m.

(a) Calculate, for the incident photon,

(i) its momentum,

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

$$p = \frac{6.63 \times 10^{-34}}{6.5 \times 10^{-12}} = 1.02 \times 10^{-22}$$

momentum = 1.02×10^{-22} Ns [2]

(ii) its energy.

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

$$= \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{6.5 \times 10^{-12}} = 3.06 \times 10^{-14}$$

energy = 3.06×10^{-14} J [2]

(b) The angle θ through which the photon is deflected is given by the expression

$$\Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

where $\Delta\lambda$ is the change in wavelength of the photon, h is the Planck constant and c is the speed of light in free space.

(i) Calculate the angle θ.

$$(6.84 - 6.50) \times 10^{-12} = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 3 \times 10^{8}}(1 - \cos\theta)$$

$$-\left[\frac{\left[(6.84 - 6.50) \times 10^{-12}\right] \times 9.1 \times 10^{-31} \times 3 \times 10^{8}}{6.63 \times 10^{-34}} - 1\right] = \cancel{-}\cos\theta$$

$$\theta = 30.7^\circ$$

θ = 30.7 ° [2]

(ii) Use energy considerations to suggest why $\Delta\lambda$ must always be positive.

Deflected photon will always have less energy and as $\downarrow E \propto \frac{1}{\lambda\uparrow}$, the wavelength will always be greater after deflection and so $\Delta\lambda$ shall always be positive.

[3]

10 (a) A metal surface is illuminated with light of a single wavelength λ.
On Fig. 10.1, sketch the variation with λ of the maximum kinetic energy E_{MAX} of the electrons emitted from the surface.
On your graph mark, with the symbol λ_0, the threshold wavelength.

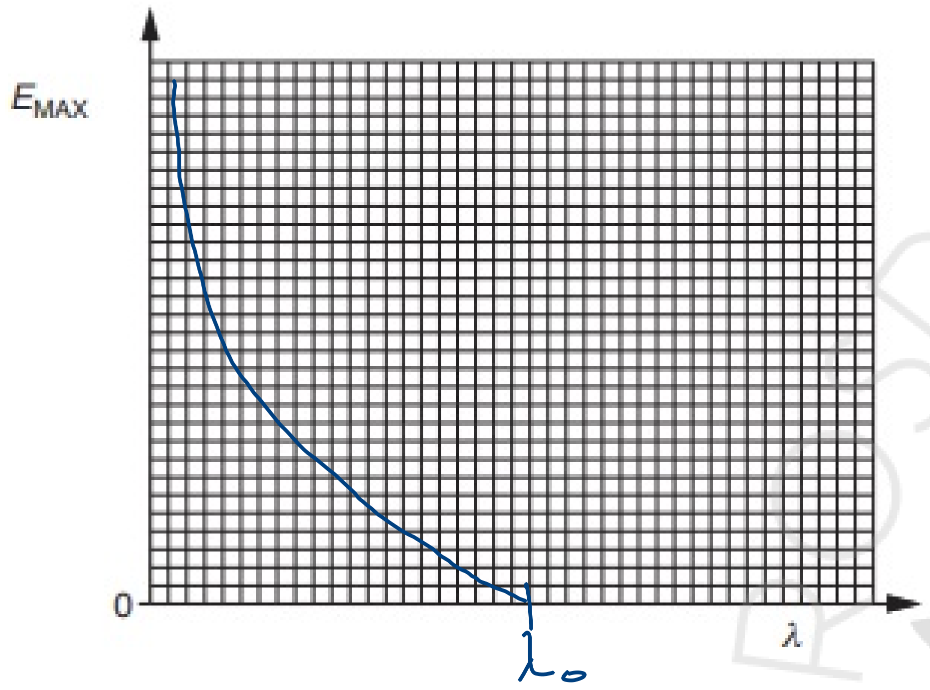


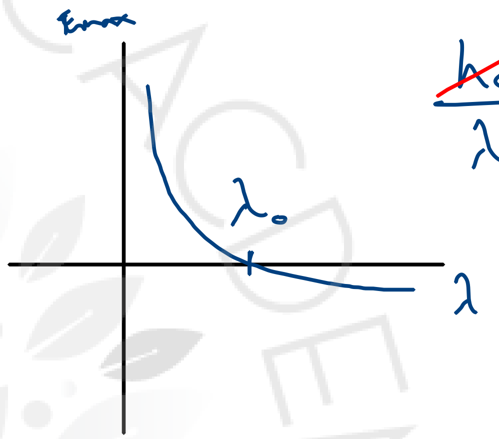
Fig. 10.1

[3]

$$E_{max} = \frac{\overbrace{hc}^{const}}{\lambda_i} - \overbrace{\frac{hc}{\lambda_0}}^{const}$$

$$E_{max} \propto \frac{1}{\lambda_i}$$

$$y \propto \frac{1}{x} - c$$



$$0 = \frac{hc}{\lambda_i} - \frac{hc}{\lambda_0}$$

$$\frac{\cancel{hc}}{\lambda_0} = \frac{\cancel{hc}}{\lambda_i}$$

$$\lambda_i = \lambda_0$$

(b) A neutron is moving in a straight line with momentum p.
The de Broglie wavelength associated with this neutron is λ.
On Fig. 10.2, sketch the variation with momentum p of the de Broglie wavelength λ.

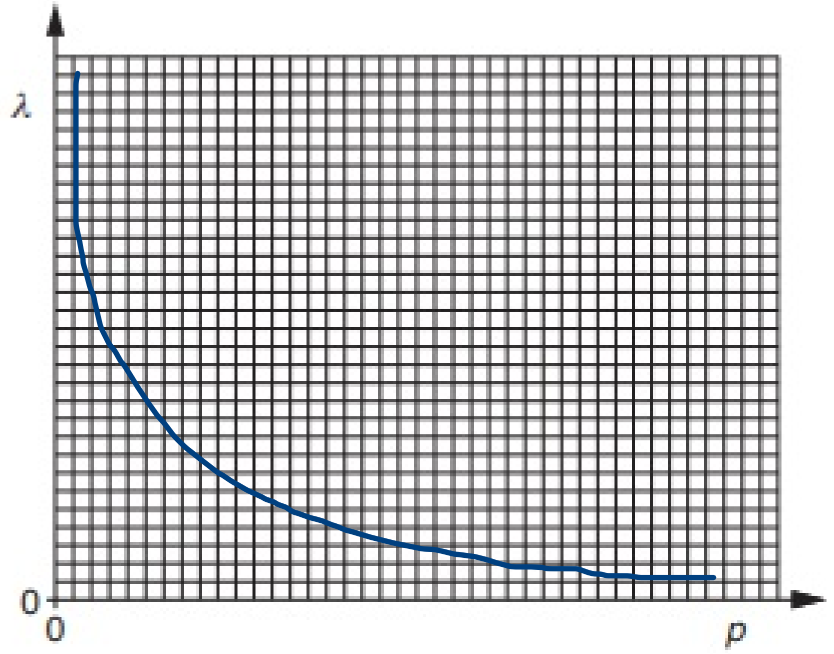


Fig. 10.2

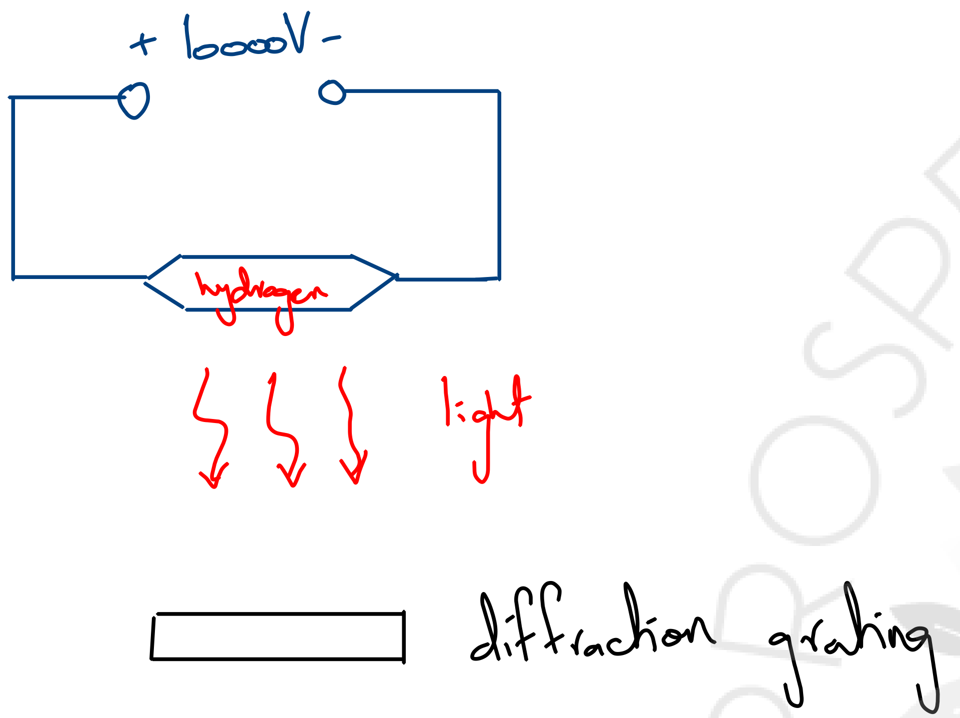
[2]

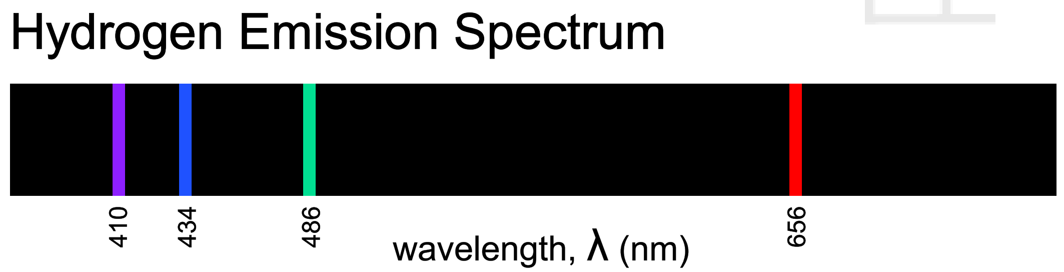
$$p = \frac{h}{\lambda}$$

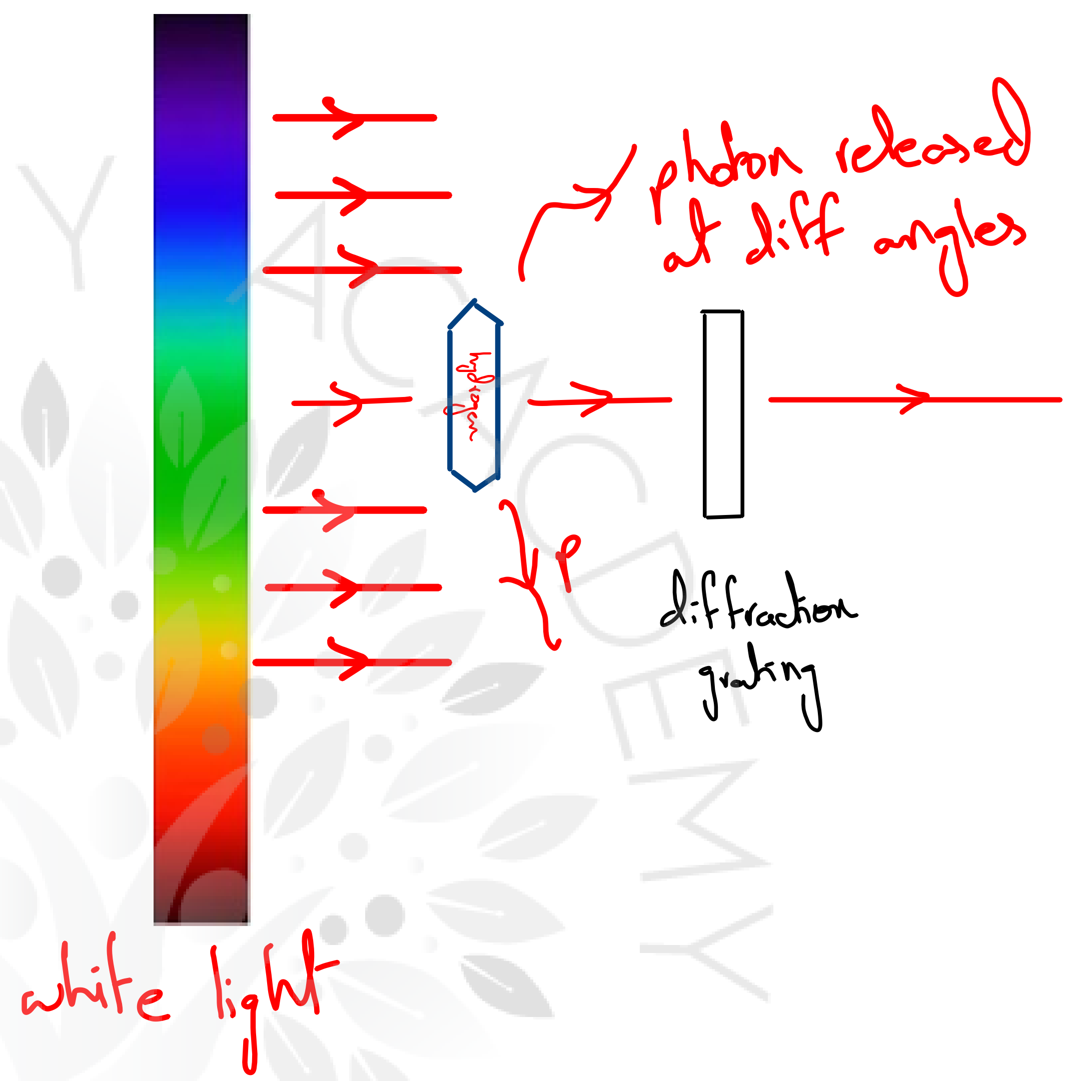
$$\lambda \propto \frac{1}{p}$$

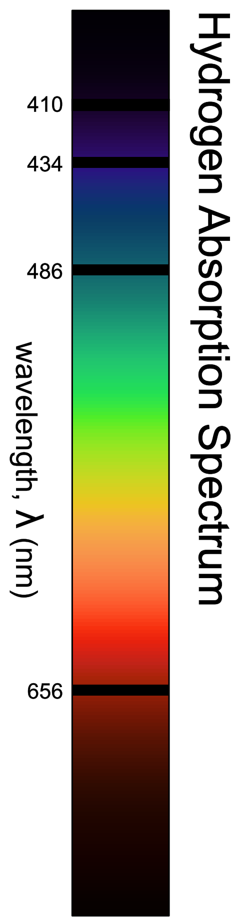
[Total: 5]

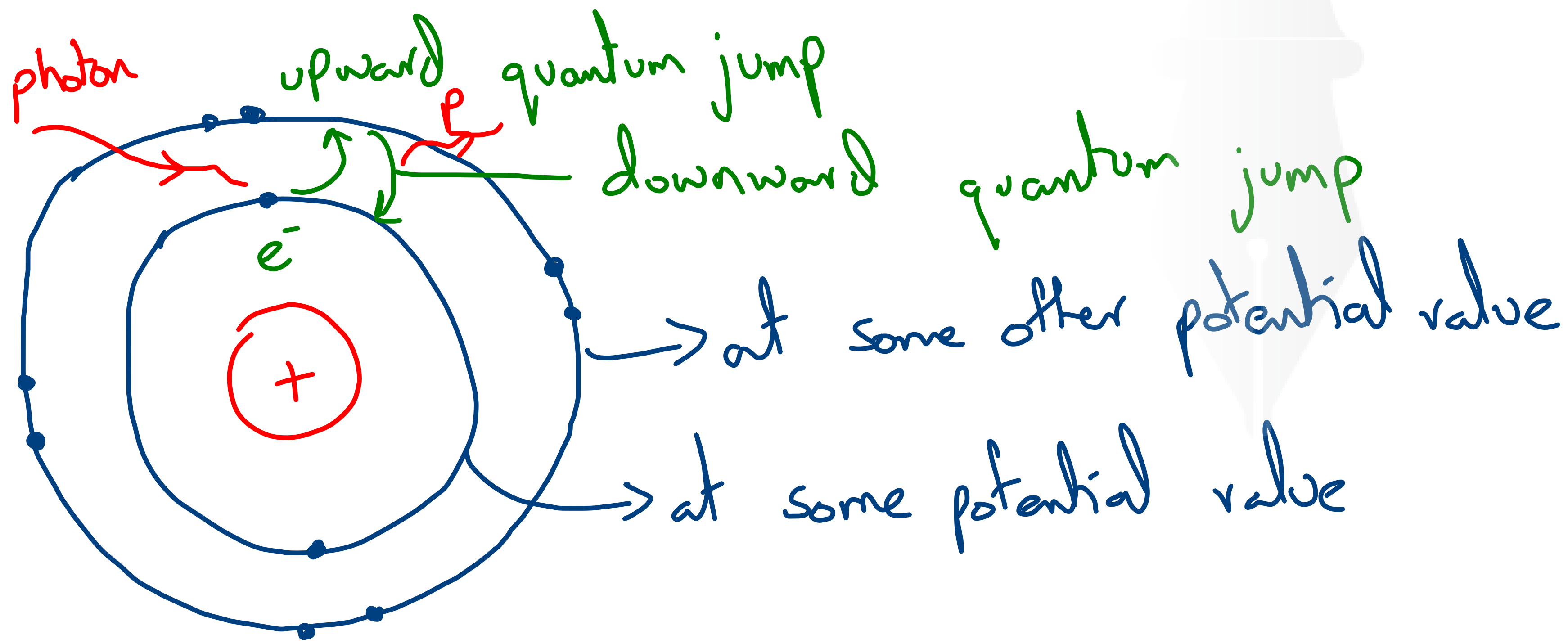
Neil Bohr's model of the atom:-





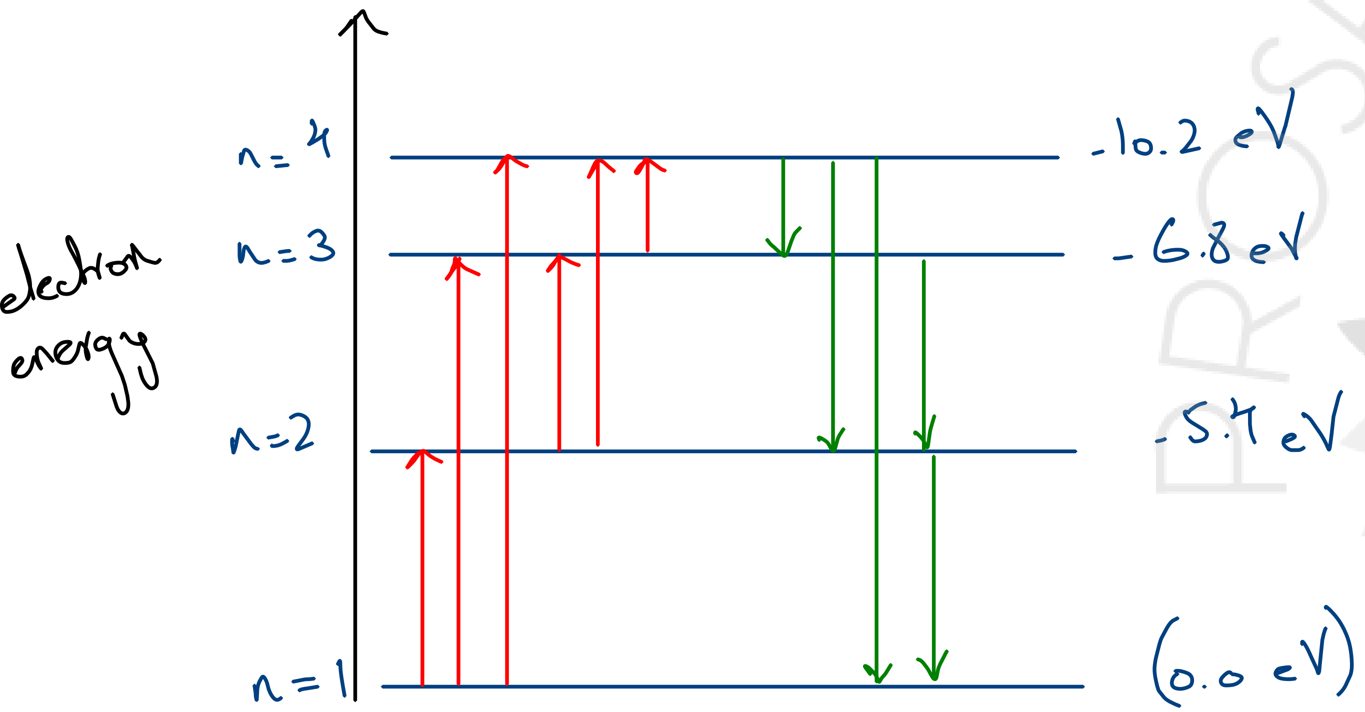






- Atoms have distinct and discrete energy levels
- These energy levels are constant to each atom

- Each energy level has a potential value (-ve because of attractive field)
- There are multiple ways, electrons can make transition / quantum jumps.
- The most stable energy level is n=1 (0.0 eV)



- Whenever an upward quantum jump happens, energy in the exact amount is absorbed
- Whenever a downward quantum happens, a photon of the corresponding energy is released.

Q. What wavelength of photon is required for a transition from n=1 to n=2 ?

$\Delta E = E_f - E_i$

$\Delta E = -5.4 - 0.0$

$\Delta E = -5.4 \text{ eV}$

$\Delta E = -5.4 \times 1.6 \times 10^{-19} = 8.64 \times 10^{-19} \text{ J} \Rightarrow E = \frac{hc}{\lambda} \Rightarrow 8.64 \times 10^{-19} = \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{\lambda}$

$\lambda = 2.30 \times 10^{-7} \text{ m}$

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

(i) the wave nature of a particle,

diffraction ....[1]

(ii) the particulate nature of electromagnetic radiation.

photo electric effect ....[1]

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

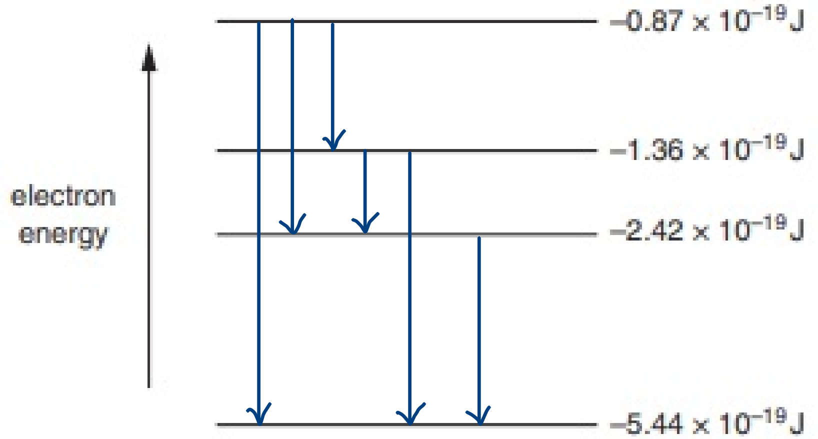


Fig. 7.1 (not to scale)

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

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

(i) state the number of lines,

6 ....[1]

(ii) calculate the minimum wavelength.

$\Delta E = E_f - E_i$

$= [5.44 - (-0.87)] \times 10^{-19}$

$= 4.57 \times 10^{-19}$

$4.57 \times 10^{-19} = \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{\lambda}$

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

wavelength = 4.35×10^{-7} m [2]

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

....

....................[2]

(b) Light in a beam has a continuous spectrum that lies within the visible region. The photons of light have energies ranging from 1.60 eV to 2.60 eV.

The beam passes through some hydrogen gas. It then passes through a diffraction grating and an absorption spectrum is observed.

(i) All of the light absorbed by the hydrogen is re-emitted. Explain why dark lines are still observed in the absorption spectrum.

photons are re-emitted in random directions ....[1]

(ii) Some of the energy levels of an electron in a hydrogen atom are illustrated in Fig. 10.1.

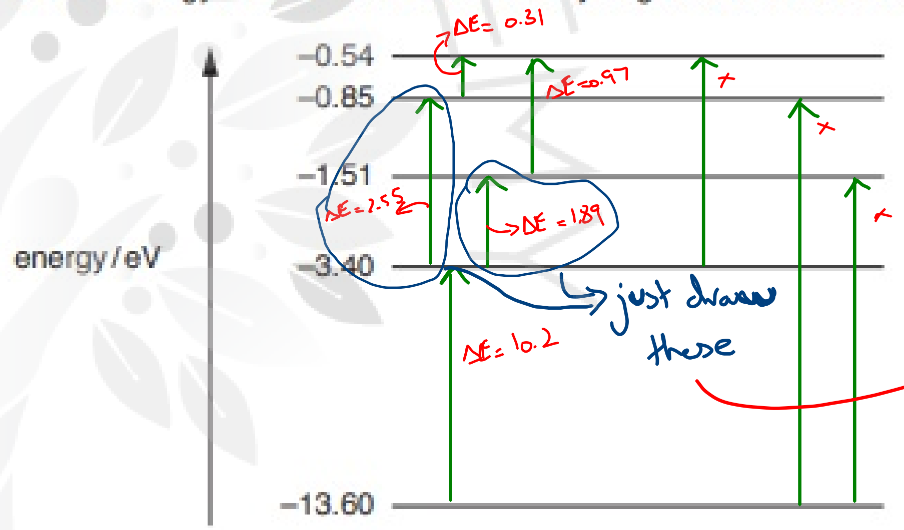


Fig. 10.1 (not to scale)

in range → 1.60 – 2.60 eV

The dark lines in the absorption spectrum are the result of electron transitions between energy levels.

On Fig. 10.1, draw arrows to show the initial electron transitions between energy levels that could give rise to dark lines in the absorption spectrum. [2]

(iii) Calculate the shortest wavelength of the light in the beam.

$\Delta E = 2.55$ eV

$\Delta E = 2.55 \times 1.6 \times 10^{-19}$ J

$2.55 \times 1.6 \times 10^{-19} = \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{\lambda}$

$\lambda = 4.875 \times 10^{-7}$

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

wavelength = 4.9×10^{-7} m [3]

[Total: 8]

7 (a) Explain how the line spectrum of hydrogen provides evidence for the existence of discrete electron energy levels in atoms.

each line in the spectrum corresponds to a specific photon energy. Photons are emitted as a result of quantum jumps. Since every jump has a specific value it provides evidence for the existence of discrete electron energy levels. [3]

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

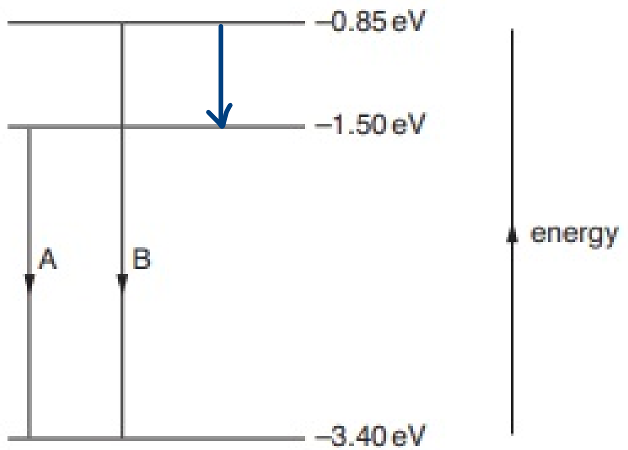


Fig. 7.1

Two possible electron transitions A and B giving rise to an emission spectrum are shown.
These electron transitions cause light of wavelengths 654 nm and 488 nm to be emitted.

(i) On Fig. 7.1, draw an arrow to show a third possible transition. [1]

(ii) Calculate the wavelength of the emitted light for the transition in **(i)**.

$\Delta E = -1.50 - (-0.85) = -0.65\,eV \times 1.6\times10^{-19}$

$= 1.04\times10^{-19}\,J$

$E = \frac{hc}{\lambda} \Rightarrow 1.04\times10^{-19} = \frac{(6.63\times10^{-34})(3\times10^{8})}{\lambda}$

$\lambda = 1.9\times10^{-6}$

wavelength = 1.9×10^{-6} m [3]

1900×10^{-9}

1900nm

(c) The light in a beam has a continuous spectrum of wavelengths from 400 nm to 700 nm. The light is incident on some cool hydrogen gas, as illustrated in Fig. 7.2.

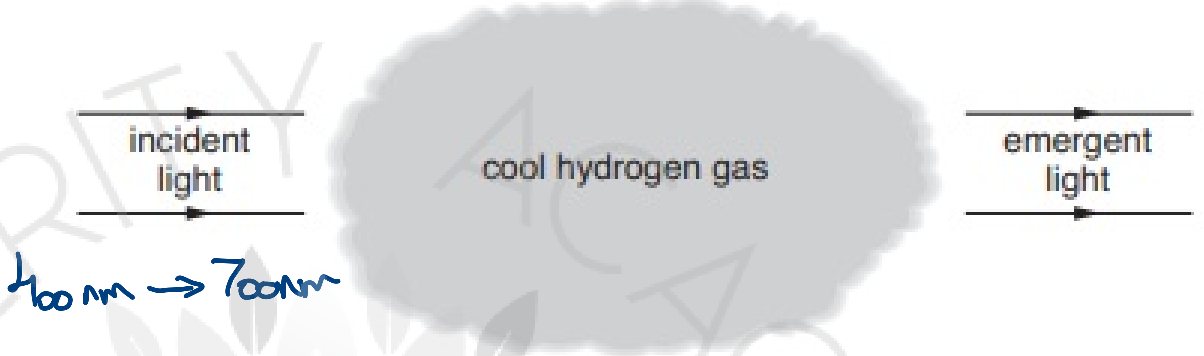


Fig. 7.2

Using the values of wavelength in **(b)**, state and explain the appearance of the spectrum of the emergent light.

Spectrum is a continuous spectrum with black lines at 654 nm and 488 nm. The electrons in hydrogen absorb a photon of energy equivalent to the respective quantum. As they get de-excited and transition downwards, they re-emit the photon in a different direction. [4]