Quantum physics

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Objective

Energy of a photon

The photoelectric effect

Wave-particle duality

Energy levels in atoms

Energy of a Photon

photon is a discrete packet {or quantum} of energy of an electromagnetic radiation/wave.

- Energy of photon can be represented by equation

$$E = hf$$

E = Energy of Photon (Joule),
h = **Planck's Constant (6.63 x 10^{-34} Js),**
f = frequency of the radiation (Hz),

Energy of a Photon

- Frequency can be represented by

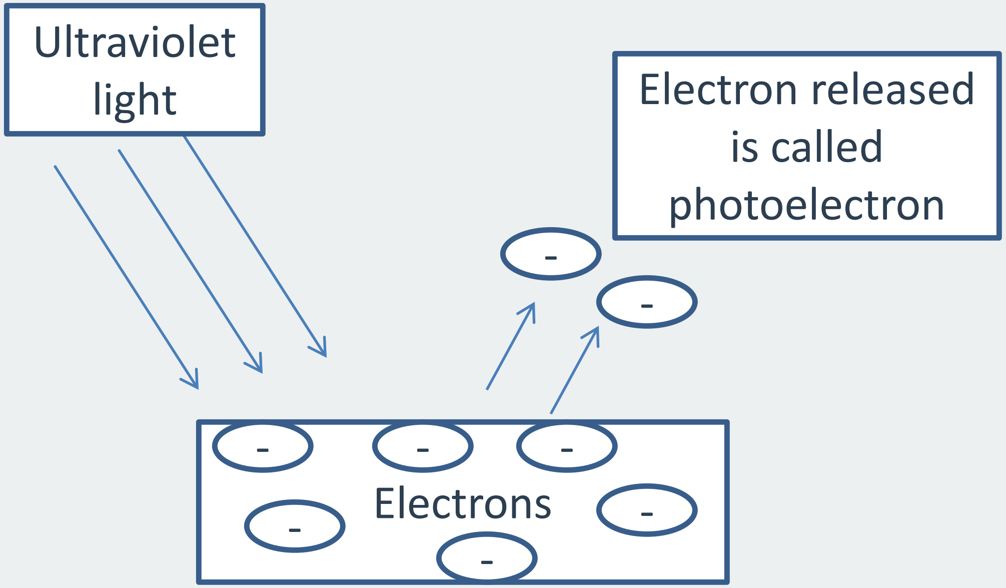
$$f = c/\lambda$$

c = speed of light in vacuum (≈ 3 x 10^8 m/s),
λ = wavelength of the radiation (m),

Energy can also be represented with ev (electron volt),

$$1 \text{ ev} = 1.602 \times 10^{-19} \text{ J}$$

Photoelectric Effect



emission of electrons from a cold metal surface when electromagnetic radiation (such as ultraviolet) of sufficiently high frequency falls on it

Photoelectric Effect

4 major observation when a clean metallic surface is exposed by by electromagnetic induction

1. No electrons are emitted if the frequency of the light is below a minimum frequency {called the **threshold frequency**}, regardless of the intensity of light
2. Rate of electron emission {ie photoelectric current} is proportional to the light intensity.

Photoelectric Effect

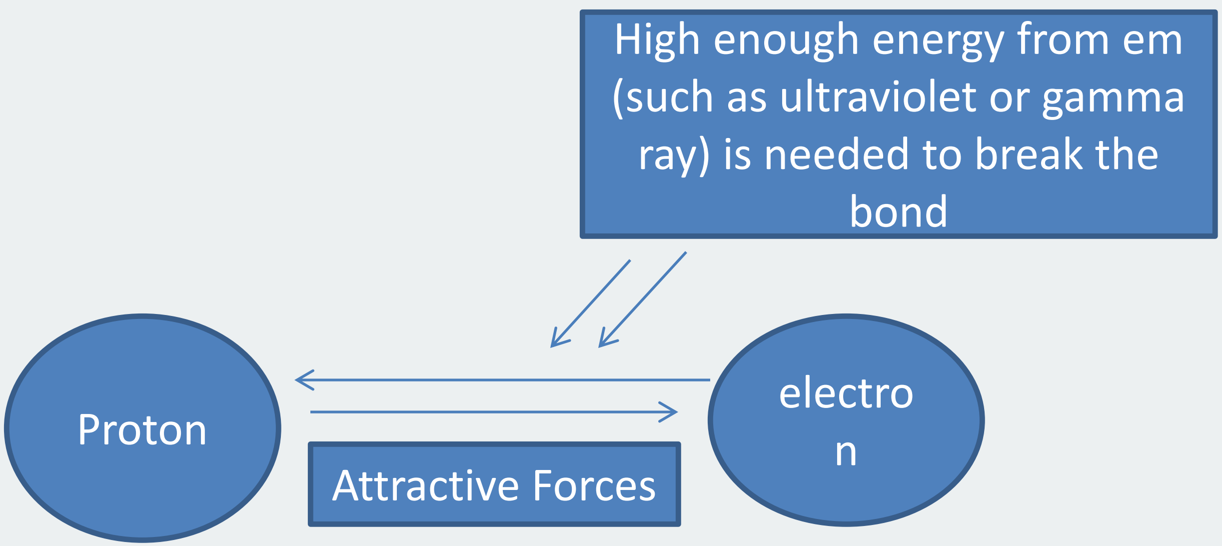
3. {Emitted electrons have a range of kinetic energy, ranging from zero to a certain maximum value. Increasing the freq increases the kinetic energies of the emitted electrons and in particular, increases the maximum kinetic energy.} **This maximum kinetic energy depends only on the frequency and the metal used {ϕ}; the intensity has no effect on the kinetic energy of the electrons**.
4. Emission of electrons begins instantaneously {i.e. no time lag between emission & illumination} even if the intensity is very low.

   NB: (1), (3) & (4) cannot be explained by Wave Theory of Light; instead they provide evidence for the particulate/particle nature of electromagnetic radiation.

Photoelectric Effect

Threshold frequency is the minimum frequency of the electromagnetic radiation required to eject an electron from a metal surface.

Work function (φ) of a metal is the minimum energy required to eject an electron from a metal surface



Photoelectric Effect

$$\phi = h\, f0 = h\, c\, \lambda 0$$

- ϕ = work function (joule or em),
- h = Planck's Constant (6.63 x 10^{-34}Js),
- f0 = treshold frequency,
- c = speed of light (in vacuum ≈ 3 x 10^{8} m/s),
- λ0 = threshold wavelength maximum

Ps: one photon can only remove one electron

Photoelectric Effect

Photoelectric effect can be represented by one equation

$$hf = \phi + \frac{1}{2} m_e v_{max}^{\;2}$$

Photon energy = work function + kinetic energy of photoelectron

Examples

A monochromatic light with a wavelength of 470 nm is exerted on a metal to produce photoelectric effect, the emission can be halted by applying a potential of 1.2 V to the metal

a) find the work function

ϕ = Photon energy - kinetic energy of photoelectron = hf – eV,

$$\phi = hc/\lambda - eV = (6.63x\ 10^{-34})\frac{(3\ x\ 10^{8})}{470\ x\ 10^{-9}} - 1.2\ x 1.602\ \mathrm{x}\ 10^{-19}$$

$\phi = 2.31\mathrm{x}\ 10^{-19}$ J

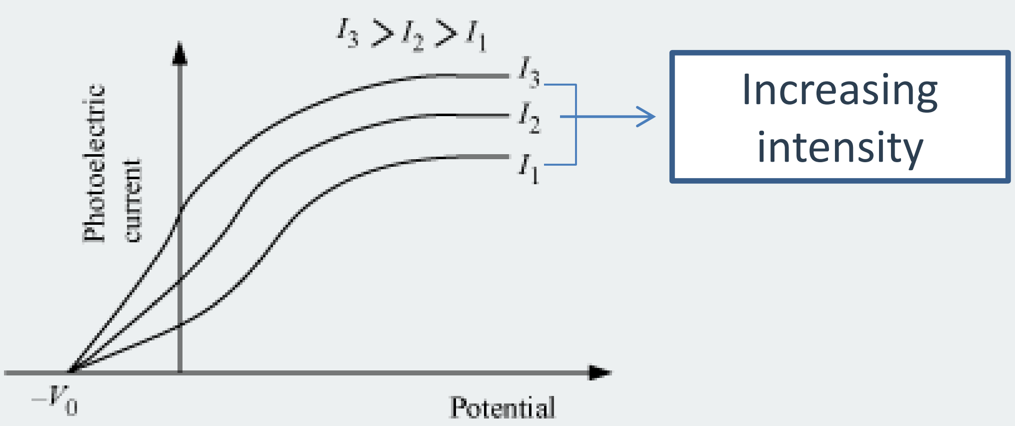
Photoelectric Effect

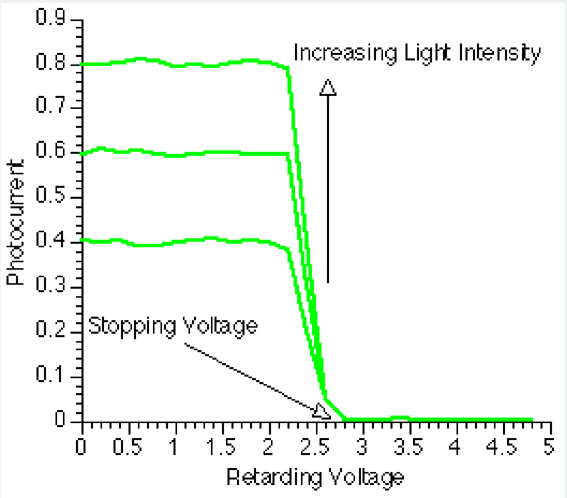
b) Maximum kinetic energy of the emitted photoelectrons

Stopping voltage = 1.2 V

= 1.2 x1.602 x 10^{-19} = 1.92 x 10^{-19} J

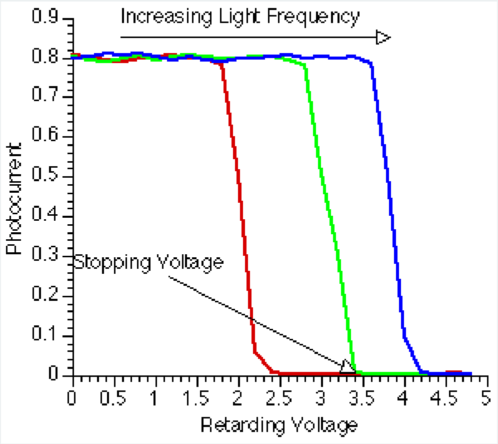
If only intensity doubles, the saturation current doubles (V_s (stopping voltage) : no change)

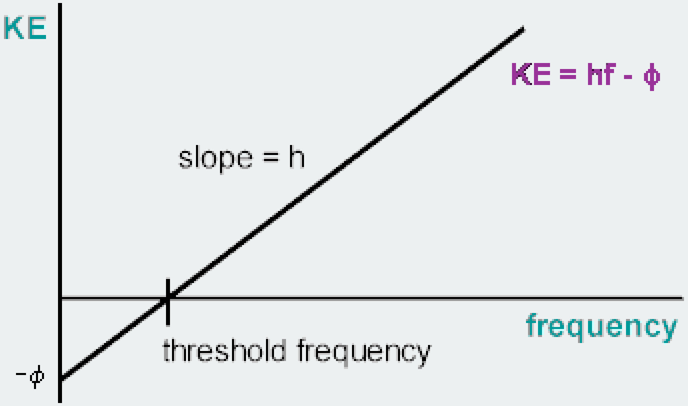




Photoelectric Effect

- If only <u>frequency</u> increases, <u>magnitude of V_s</u> also increases, thus no change to saturation current.





Photoelectric Effect

- **Intensity = Incident Power / Illuminated Area = (N/t)(hc/λ)(1/Area)**
- Thereby **Intensity ∝ Rate of incidence of photons, N/t** {for a given λ}
- Photocurrent **I = (n/t)e**, where **(n/t) = rate of emission of electrons**
- **Why rate of emission of electrons << rate of incidence of photons {for $f>f_0$}:**
- Not every photon would collide with an electron; **most are reflected by the metal or miss hitting any electron**.
- On the way out to the metal surface, an electron may lose its kinetic energy to ions and other electrons it encounters along the way. This energy loss prevents it from overcoming the work function.

Wave Particle Duality

- Light and matter {such as electrons} have both wave & particle properties.
- **De Broglie** equation state that the wavelength of matter can be represented by the equation below

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

and **f is proportional to kinetic energy of the particle**

where p is momentum of the particle, $p = mv$,

λ = wavelength of the matter wave (meter),

h = planck constant,

p = momentum of the particle (kg m/s),

m = mass of the particle (kg),

v = velocity of the particle (m/s),

f = frequency (Hz)

Wave Particle Duality

- Interference and diffraction provide evidence for the wave nature of E.M. (electromagnetic) radiation.
- Photoelectric effect provides evidence for the particulate nature of E.M. radiation.
- These evidences led to the concept of the **wave-particle duality of light**.
- **Electron diffraction** provides evidence that *matter* / particles have also a wave nature & thus, have a dual nature.

Wave Particle Duality

Example

Ultraviolet light with wavelength 10.1 nm is shone on clean metal surface, the work function of the metal is 3.35 eV. Determine

- The maximum energy of the photoelectrons

Ans: KE = hf – ϕ = $6.63 \text{ x } 10^{-34} \frac{(3\text{x } 10^{8})}{10.1 \, x \, 10^{-9}} - 3.35 \, x \, 1.6 \, x \, 10^{-19} = 1.92 \, x \, 10^{-17}$

- Maximum speed of the photoelectrons

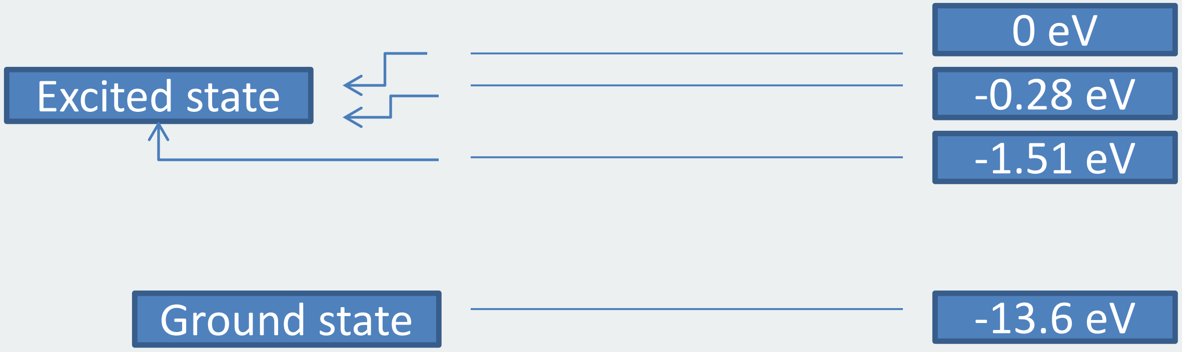
Ans: $0.5Mv^2 = 1.92 \, x \, 10^{-17}, M = 9.1 \, x 10^{-31}$

Hence v = $6.49 \, x \, 10^{6} \frac{m}{s}$

- Calculate De Broglie wavelength

Ans: $\lambda = \frac{h}{p} = \frac{6.63 \, x 10^{-34}}{6.49 \, x \, 10^{6} x \, 9.1 \, x \, 10^{-31}}$ = $1.12 \text{ x } 10^{-10} \, m$

Energy Levels in an Atom



Key point

- All energy levels are negative, energy outside the atom is taken as zero
- **Ground state** is the most stable and the lowest energy level of the atom. Other energy level called **excited states**
- **Ionisation potential** is the p.d. required to remove an electron from the atom
- **Ionisation energy** the energy required to be absorbed to remove an electron from the atom
- **Excitation potential** is p.d. required to move the electron from ground state to excited state.

Energy Level in an Atom

- Photon will be released or absorbed when electron make a transition in energy level

$$\Delta E = E(\boldsymbol{initial}) - E(\boldsymbol{final}) = hf$$

Allowed energy level depends on the magnitude of angular momentum

$$L = \frac{n.h}{2\pi}$$

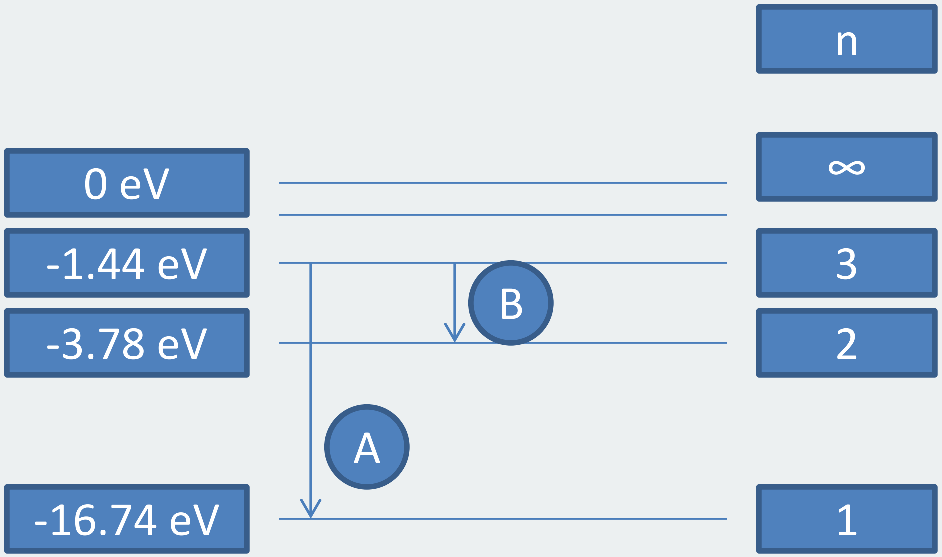
L = angular momentum of the electron

n = 1,2,3, ….. (principal quantum number)

For the equation above assume the lowest value of n is 1 which corresponds smallest possible radius of 0.0529 nm (**Bohr Radius**)

Energy Level in an Atom

Example



Calculate the wavelength for transition A and B
Ans: for A, ΔE = -1.44 – (-16.78) = 15.34 eV

Energy Level in an Atom

1534 eV = $\frac{hc}{\lambda}$, λ =$6.63 \text{ x } 10^{-34}\text{x } \frac{3 \text{ x } 10^{8}}{15.34 \text{ x } (1.6 \text{ x } 10^{-19})}$ = $8\ x\ 10^{-8}$ m

For B, ΔE = - 1.44 – (-3.78) = 2.34 eV

$\lambda = 5.31 \text{ x } 10^{-7}\ \ m$

How much energy required to ionize the atom in its ground state?

Ans: 0 - (-16.74) = 16.74 eV

References

- http://www.xtremepapers.com/revision/a-level/physics/quantum_physics.php
- a-level *comple* guide, thomas bond, chris hughes, THEMIS.
- http://www.meritnation.com/img/lp/1/12/16/255/913/1838/1880/8-6-09_LP_Vandana_Phy_1.12.4.11.1.1_srav_SS_html_m336ef716.png