Quantum Physics

IB 12

Properties of photons: Quantum of energy – "particle" of light

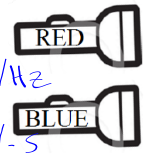
'pure' energy, m = 0, v = c (in a vacuum), q = 0, has momentum

Energy of a Photon

$E \propto \nu$ $\quad E = hf = h\frac{c}{\lambda}$

$h = 6.63\times10^{-34}\,J/Hz$

$= 4.14\times10^{-15}\,eV\cdot s$



$E^2 = p^2c^2 + \cancel{m_0^2c^4}$

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

1. A beam of red light from a laser light has a frequency of 4.4 x 10^{14} Hz.
   a) Determine the energy of each photon of this light in both joules and electron-volts.

   $E = hf = 6.63\times10^{-34}\,J.s \cdot 4.4\times10^{+14}\,Hz = 2.9\times10^{-19}\,J$

   $(4.14\times10^{-15}\,eV.s)$ " $= 1.8\,eV$

   b) Write expressions for the energy of a photon both in joules and in electronvolts.

   $hf/(1e.c.)$

   c) How many photons are in one joule of this laser light?

   $E_{TOT} = N_{photons} \times E_{photon}$

   $N = \frac{E_T}{E_{photon}} = \frac{1J}{2.9\times10^{-19}\,J/photon} = 3.4\times10^{18}$

2. Which contains more photons: one joule of red light or one joule of blue light? Explain.

   $\uparrow N = E_T/E_{photon}\downarrow$

Power – energy per unit time

Formula: $P = E/t$

Units: $[J/s] = [W]$

Intensity – power per unit area

Formula: $I = P/A$

Units: $[W/m^2]$

3. Light from a 2.5 mW laser has a wavelength of 670 nm. How many photons does it emit in 3.0 minutes?

$f = c/\lambda$

$E_{photon} = hf$

$E_T = P \cdot t = N \times E_{photon}$

$$N = \frac{2.5\times10^{-3}\,\cancel{J}/\cancel{s} \times 180\,\cancel{s}}{6.63\times10^{-34}\,\cancel{J}\cdot\cancel{s} \cdot \frac{3\times10^{8}\,\cancel{m}/\cancel{s}}{670\times10^{-9}\,\cancel{m}}}$$

1.5×10^{18} photons

When light shines from a given source (flashlight, laser, etc.):	Energy of each photon	Total energy	Number of photons
If the frequency of the light is constant, as the intensity of the light increases….	remains the same	increases	increases
If the intensity of the light is constant, as the frequency of the light increases….	increases	remains the same	decreases

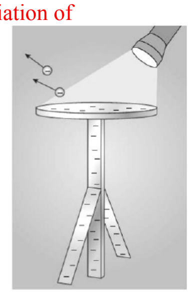
remains the same increases decreases

4. Compare the concept of light's intensity if light is viewed as a wave to that if it is viewed as a particle.

Wave: The energy of a wave depends on its intensity (amplitude), not its frequency so more intense light has more energy per wave.

Particle: Photon energy depends on frequency not intensity.
Intensity measures total energy (total number of photons).

The Photoelectric Effect: the emission of electrons from a metal when electromagnetic radiation of high enough frequency (or low enough wavelength) falls on the surface



The Experiment:

1. Light of varying frequencies and intensities are shone on a metal surface (photoemissive surface).
2. Light below a certain frequency will not emit electrons (photo-electrons) no matter how intense it is or how long it shines on the surface. Light at or above a certain frequency will immediately emit electrons no matter how intense it is.

Threshold (minimum) frequency (f_0):

minimum frequency of light needed to eject electrons from the surface of the metal

Threshold (maximum) wavelength (λ_0):

maximum wavelength of light needed to eject electrons from the surface of the metal

How are these results in conflict with the classical theory about light?

Classical Theory says . . . light acts as a wave and the energy of a wave depends on its amplitude (intensity) not its frequency.

	Classical predictions	Experimental evidence
Whether electrons are ejected or not depends on . . .	Intensity of the light (If intense enough, electrons will be ejected no matter what the frequency)	Frequency of the light
The maximum kinetic energy of the ejected electrons depends on . . .	Intensity of the light	Frequency of the light
At low intensities, ejecting electrons . . .	Takes time	Occurs instantaneously above threshold frequency but never below certain frequency

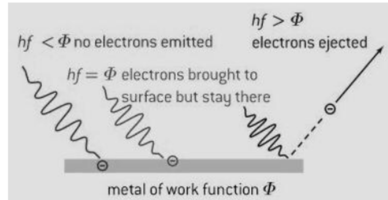
Wave-Particle duality: Different properties of light (or matter) can be more clearly explained by using either the wave or the particle model.

	Wave Nature	Particle Nature
Light (Energy)	- Diffraction - Interference - Doppler Effect - Polarization	Photo-electric Effect
Matter	- Electron Diffraction - Matter Waves	Collisions (e.g. Alpha particle scattering)

Einstein's explanation of the photo-electric effect:

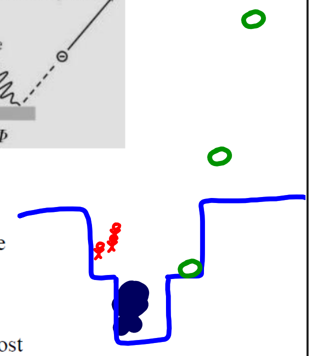
i) Light acts like a particle (not a wave) in which its energy is proportional to its frequency.

ii) Electrons at the surface of the metal need *a minimum energy in order to be ejected from the surface*, called the ***work function***, an amount which varies from metal to metal. (Electrons below the surface of the metal need more energy to be emitted.)



Work Function (ϕ): $\phi = hf_0$

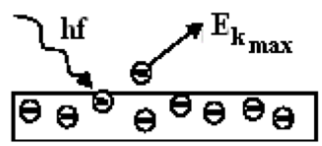
iii) There is a one-to-one interaction in which one electron absorbs one photon. If the photon has enough energy (high enough frequency) to overcome the work function, the electron will leave surface immediately with no time delay. If not, the electron will still absorb the photon but will remain bound to the metal.



iv) Any "extra" energy (above the work function) is retained by the electron in the form of kinetic energy. The maximum kinetic energy (E_{kmax}) is retained by electrons that were most loosely held on the very surface of the metal.

v) The number of photons arriving per second, and therefore the rate of emission of electrons, is determined by the intensity of the light, not its frequency. The intensity of the light plays no role in the energy each photon has.

Einstein's Photoelectric Effect Equation: $E_{photon} = \phi + E_{k\,max}$



1. Photons strike a metal surface whose work function is 2.1 electronvolts, ejecting electrons with a maximum kinetic energy of 7.5 electronvolts.

a) Find the energy of the photons.

$9.6\ eV = hf$

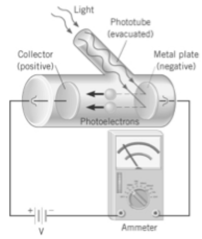
b) Find the threshold frequency of the metal.

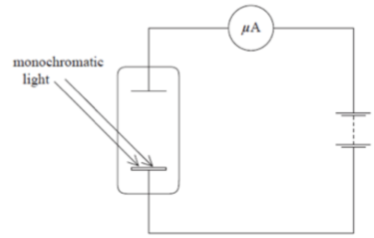
$2.1\ eV = hf_0$

h in eV·s

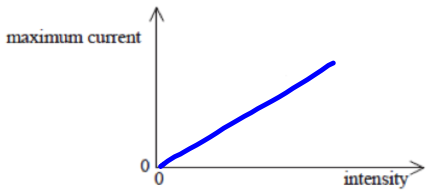
Analysis of the Photo-Electric Effect Experimental Data

Monochromatic light is incident on a metal surface in a photo-cell as shown. The frequency of the light is above the threshold frequency for this metal. The current in the photo-cell is measured using a microammeter. The potential difference of the voltage source is varied until the reading on the microammeter is a maximum (called the "saturation current.")





1. Sketch a graph of how this maximum current varies with the intensity of light if the frequency of the light is kept constant.



Explanation:

-Intensity of light is proportional to number of photons per second striking plate
-Each photon ejects an electron
-So current is proportional to intensity

2. Describe and explain what will happen to the current if the intensity is kept the same but the frequency of the light is increased. Sketch the resulting graph on the axes above.

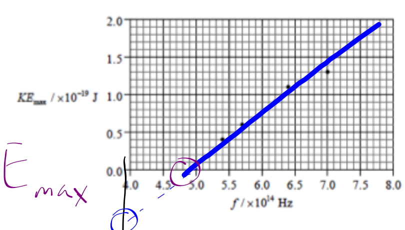
Less current since total energy is constant but the energy per photon has increased – so fewer photons are striking the metal per second and fewer electrons are ejected

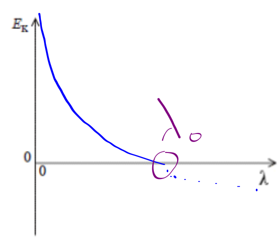
A plot of the maximum kinetic energy of the ejected electrons versus frequency of the incident light is shown. Discuss the features of this graph. Sketch a graph of maximum kinetic energy versus wavelength.

Mathematical Model

$E_{photon} = \phi + KE_{max}$

$E_{Kmax} = hf_o - \phi$





x-intercept = f_o

Slope = h

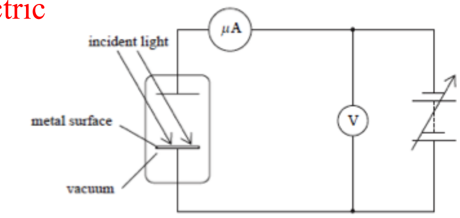
y-intercept = $-\phi$

Millikan's Stopping Potential Experiment

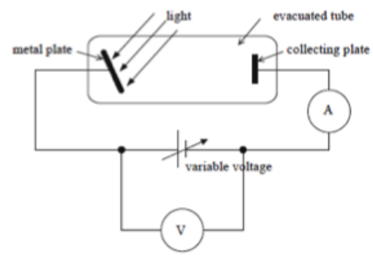
Purpose: to test Einstein's model of the photo-electric effect

Method:

1) Make collecting plate (electrode) negative to repel electrons emitted from the surface (reverse the normal polarity).
2) Increase the potential difference until the current drops to zero.
3) Electrons emitted from metal surface have a maximum energy. If this maximum energy is less than the energy required for electrons to move between plates (against the potential difference), electrons will not reach the collecting plate.



Two comparable schematics of the stopping potential experimental apparatus



Stopping Potential (V_s):

1) minimum potential difference that stops all current
2) reading on voltmeter equal to KE max in electronvolts

Maximum kinetic energy of ejected electrons (E_{max}): $E_{k_{max}} = qV_s$

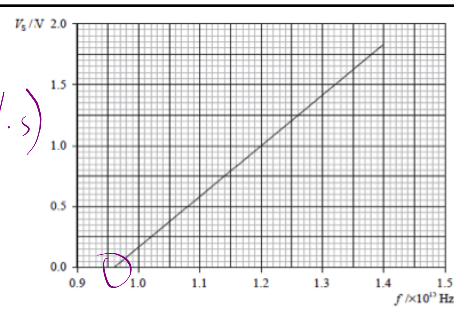
Mathematical Model

$$\frac{hf}{q} = \frac{hf_0}{q} + \underbrace{V_s}_{E_{kmax}}$$

x-intercept = f_0

Slope = h (in eV·s)

y-intercept = ϕ in eV



Use the graph above to determine a value for the work function in electronvolts and for Planck's constant.