How are Light & Matter Similar?

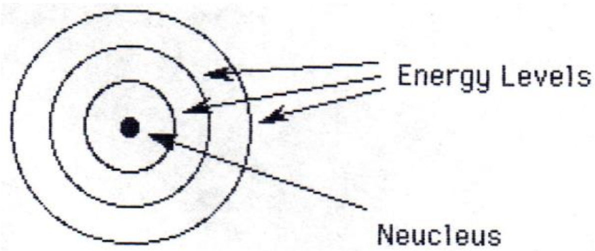
Reference: Heinemann Physics 12 4th Edn Chapter 10 Page 330

Physics with Synno – Light-Matter – Lesson 1

L&M.1 The Photoelectric Effect

L&M.1.1 The Bohr Theory

Early last century the theory postulated by Niels Bohr, about the structure of the atom was generally accepted. Bohr's theory said that electrons in an atom have fixed energy levels and can move between energy levels provided they are given the correct amount of energy.



In 1925 Frank and Hertz designed an experiment to test the predictions of the Bohr Theory. Their results coincided with the theory and they received the Nobel prize for their efforts.

L&M.1.2 Quanta

Bohr also postulated that electrons could jump from one stable energy level to another of lower energy. This would follow with the emission of a discrete package of energy called QUANTA. The value of this quantum of energy was given by the difference in energy of the two levels. It was also noted that these quanta of energy often appeared as light. The quanta of energy emitted in these situations are called PHOTONS. He used Max Plank's equation to calculate the energy of the photon.

$$E_{photon} = h\,f$$

Combining this with the wave equation for light $c = \lambda\,f$ we get:

$$E = \frac{h\,c}{\lambda}$$

where h is Plank's constant = 6.6×10^{-34} J s or $4.1{\times}10^{-15}\ eV\,s$

Note: Another unit for measuring energy is the **electron volt** (eV), the amount of energy *an electron* gains on moving through a potential of 1 V. It is a tiny fraction of a joule.

1 eV represents the *energy* that a single electron would gain after being moved through a potential of 1 V.

1 eV = 1.6×10^{-19} J

To convert Joule (J) into electron-Volt (eV), DIVIDE by 1.6×10^{-19}
To convert electron-Volt (eV) into Joule (J), MULTIPLY by 1.6×10^{-19}

Example 1:
Calculate the energy, in joule, of a photon of ultraviolet light with frequency 7.4×10^{14} Hz.

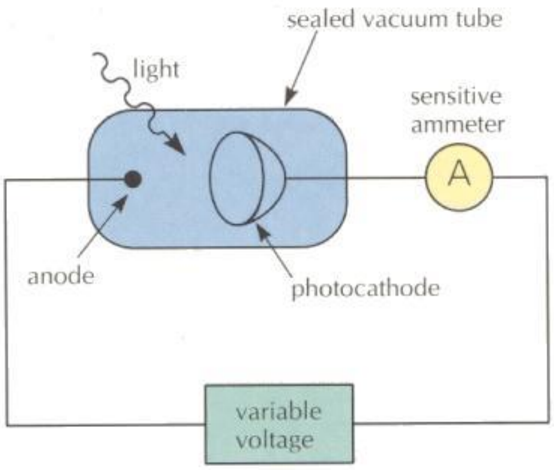
$$E_{photon} = h\,f$$
$$E_{photon} = 6.6 \times 10^{-34} \times 7.4 \times 10^{14}$$
$$E_{photon} = 4.9 \times 10^{-19}\,J$$

Example 2:
What is the energy, in electron volt, of a photon of red light of wavelength 640 nm.

$$E = \frac{h\,c}{\lambda}$$
$$E = \frac{4.1\times10^{-15} \times 3.0\times10^{8}}{640\times10^{-9}}$$
$$E = 1.92\,eV$$

L&M.1.3 The Photoelectric Effect

If photons are released from atoms when electrons drop down energy levels could the opposite also occur? The answer is yes, however, it will only occur if the energy of the incoming photon equals the difference in the atoms energy levels. Then the energy of the photon is absorbed, the electron jumps up to its new energy level and the photon ceases to exist. If the energy of the incoming photon does not exactly equal the energy difference of any of the atoms levels, it will not be absorbed.
If a photon with a large enough energy strikes an atom, an electron may be completely removed from the atom. This is called the photoelectric effect. (It is the principle by which photoelectric solar cells generate electricity).



Light radiation falling on the cathode causes emission of electrons, photoelectrons, which are then attracted to the positively charged anode. Thus a current flows. However a current is recorded even when V = 0.

If the photon incident on the plate has sufficient energy, it will raise the electron up through the energy levels and away from the atom. So the incident photon must carry enough energy to ionise the atom and give the electron some energy so that it can move away.

It was found that even if V is reversed, so that there is a retarding potential across the plates, a current still flowed. i.e. some of the photoelectrons leave the cathode with sufficient kinetic energy to reach, the now negative, anode against the retarding potential.

For a given frequency of light there will be a range of kinetic energies of the photoelectrons. This will depend on which energy level the electron comes from. If we adjust the retarding potential until it is just large enough to stop any current flowing in the circuit then we will have stopped the most energetic photoelectrons. If this happens at V_0 for electrons of charge q then we have a measure of the maximum kinetic energy of the ejected electrons, for that frequency of light.

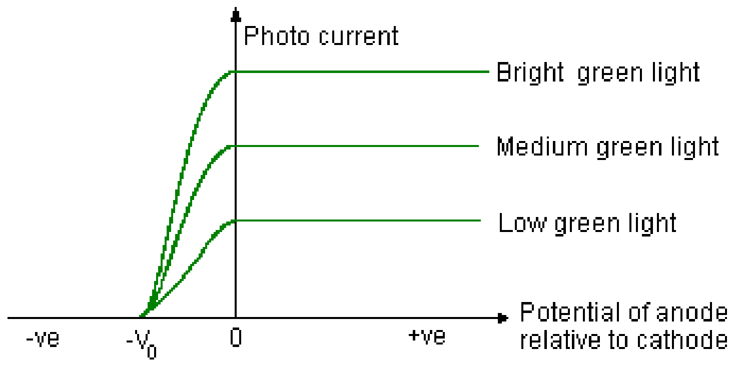
i.e. KE_{max} = work done to stop photoelectron
$= q V_0$

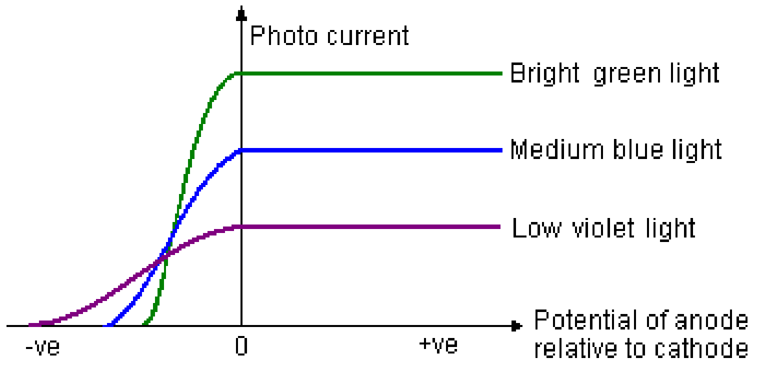
so K.E. $= q V_0$ units electron volt (or joule)

The size of the current I is dependent on the intensity of the light. i.e. increasing the intensity of the light source increases the number of electrons emitted but not their energy. This is supported by two pieces of theory.

1. **Higher intensity** means **more photons** not more energy for an individual photon.

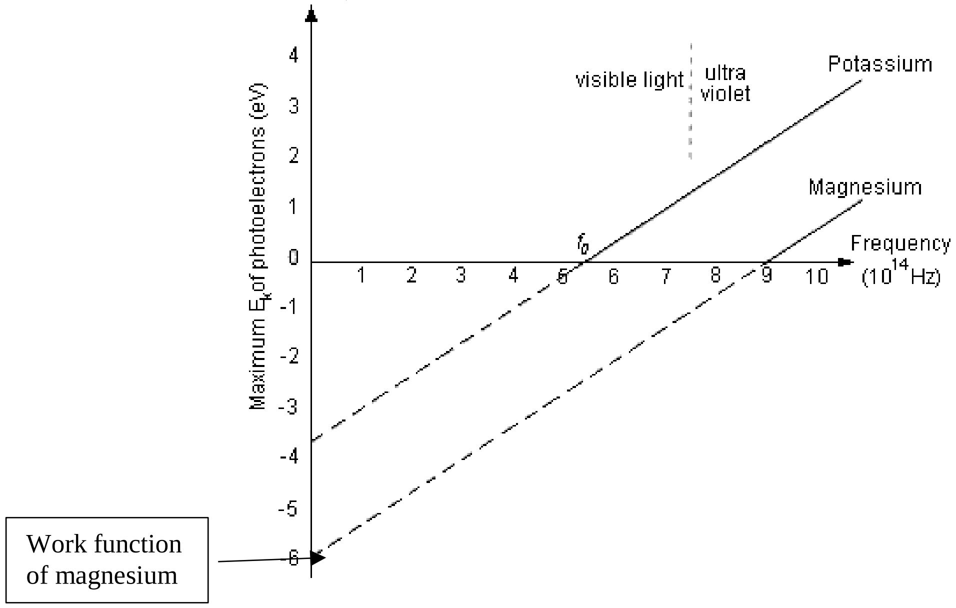
2. A photon **must give up all** of its energy to one electron it cannot be shared.





This graph shows that increasing V does increase I but the current soon reaches a maximum value called the saturation current.

Plotting maximum K.E. of photoelectrons against frequency of incident light yields - (from different cathode materials).



The following can be deduced:

- There is a threshold frequency below which the electrons are not emitted.
- Different metals have different threshold frequencies
- The gradient of the graph is the same for all metals.
- The equation of the graph, an energy equation, is $E_k = hf - W$ where E_k is the Kinetic Energy of the ejected electrons, h a universal constant and W a constant for the material. This can be written as $hf = E_k + W$
- W is either called the work function or the binding energy of the metal.
- If the graph is extrapolated back to the vertical axis. The point of intersection is the work function.

Note: Your text and the study design use ϕ as the symbol for the work function.

<u>Summarizing these results:</u>

1. The stronger the beam of light of a given color (*f*) the greater the photoelectric current.

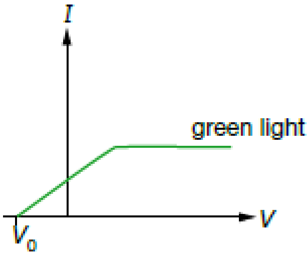
2. For each type of material used for the cathode, photoelectrons are not ejected if light has a frequency below a certain value called the threshold frequency (f_0). This threshold frequency is a characteristic of the metal.

3. The maximum kinetic energy of the emitted electrons increases in direct proportion to the frequency of the incident light and does not depend on the intensity of the light source.

4. The emission of electrons is immediate ($<10^{-9}$ sec), no matter how weak the light source, provided the frequency is above the threshold frequency of the cathode material.

Example

A sample of potassium is used as the cathode of a photocell with which the photoelectric effect is studied. When green light of a particular intensity is shone onto the cathode, the following *I*–*V* graph is obtained. Also, the threshold frequency for this sample is found to lie in the yellow region of the visible spectrum.

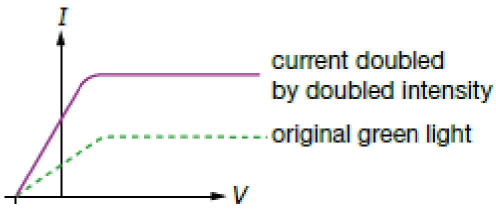


a What current reading would be expected if red light was shone onto the cathode?
b Draw the *I*–*V* graph that would result if the intensity of the incident green light was doubled.
c Draw the *I*–*V* graph that would result if violet light of a very low intensity was incident upon the cathode.
d When UV light is incident upon the cathode, the stopping voltage is found to be 2.25 V. Determine the maximum kinetic energy of the photoelectrons in *joules* and *electron volts*.

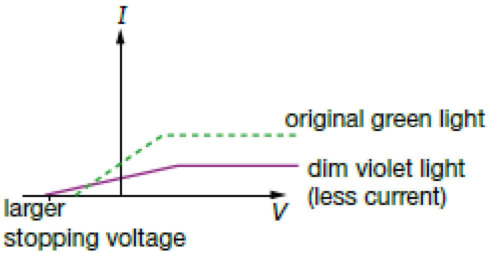
Solution

a Since red light corresponds to light of a lesser frequency than the threshold frequency (yellow light), no current will be observed.

b



c



d Working in joules:

$E_k(\text{max}) = eV_0$ (joules)

$= 1.6 \times 10^{-19} \times 2.25$

$= 3.6 \times 10^{-19}$ J

Working in electron volts:

$E_k(\text{max}) = 2.25$ eV (by definition of the electron volt)

L&M.1.4 Conflicts Between These Results and Classical Theory

1. The most puzzling feature of these results is the immediate ejection of electrons even for very weak light. According to the classical theory a wave delivers energy continuously. An electron cannot be ejected until it absorbs enough energy to free it from the atom. So according to classical theory the radiation would need to deliver energy for a finite time until the electron received enough energy to escape.

2. According to classical theory of Electro Magnetic radiation the energy of a wave is proportional to its intensity. Why is there then a threshold frequency below which electrons cannot be ejected, no matter how bright the light?

3. A more intense light should increase the energy of the ejected electrons but their K.E. depends not on intensity but upon frequency.

Example

A100 W light globe produces yellow–green light of wavelength 500 nm. Determine the number of photons released from the globe every minute.

Solution

The globe will release a total energy of $E = Pt = 100 \times 60 = 6000$ J in 1 minute.

This energy is carried by N photons, and the energy of each photon will be given by $h\,f$,

so the total energy will be $E = N\,h\,f$,

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

$$E = \frac{N\,h\,c}{\lambda}$$

Rearranging, this gives:

$$N = \frac{E\,\lambda}{h\,c}$$

$$N = \frac{6000 \times 5.0 \times 10^{-7}}{6.63 \times 10^{-34} \times 3.0 \times 10^{8}}$$

$N = 1.5 \times 10^{22}$ photons emitted each minute

Text Questions: Page 337 Exercise 10.1 All Questions