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Area Of Study 2, Interactions Of Light And Matter, Study Notes 2

The Photoelectric Effect

Some materials, mostly metals, when struck by electromagnetic radiation, emit electrons from their surface. This is the photoelectric ("PE") effect.

Light is electromagnetic radiation, so light can cause the PE effect.

Electrons have mass, and velocity when ejected from the surface of a material, and therefore have momentum. This momentum can only come from a collision between particles, so the PE effect suggests that electromagnetic radiation, and hence light, to be made from particles, despite being shown to act as a wave by diffracting and forming interference patterns.

Photoelectrons are the same as all other electrons. They're called photoelectrons because they're electrons that have been ejected from the surface of a material due to the PE effect.

Threshold Frequency, $\mathbf{f_0}$, is the frequency of electromagnetic radiation at which a material will begin to emit photoelectrons. Every material that demonstrates the PE effect has its own unique f_0.

Photoelectron Kinetic Energy (E_K), Retarding Voltage, And Stopping Voltage (V_0)

As they have mass, velocity and therefore momentum, photoelectrons also have Kinetic Energy, E_K

Each electron has a charge of 1.6×10^{-19}C.

Voltage is an amount of electrical energy per unit of charge.

Retarding voltage is voltage applied to oppose the PE effect, and hence reduce the E_K of photoelectrons.

Stopping voltage, $\mathbf{V_0}$, is the level of retarding voltage at which the E_K of photoelectrons is reduced to zero.

Stopping voltage is therefore equal to the maximum E_K of the photoelectrons, in electron Volts, eV.

$$V_0 = E_K$$

Where V_0 = stopping voltage, in V
E_K = maximum kinetic energy of photoelectrons, in eV

Electron Volts, **eV**, is a unit of energy alternate to Joules, J. **1eV is the amount of energy required to accelerate 1 electron (a charge of 1.6×10^{-19}C) across a potential difference of 1V**. Electron Volts is a simpler unit because it allows direct equivalence between V_0 and E_K, and it's much smaller than J. J, however, remains as the standard international unit for energy, so eV must be converted to J when substituting values into formulæ which include other standard international units.

$$1\text{eV} = 1.6\times10^{-19}\,\text{J}$$

Intensity, Frequency And E_K

Greater intensity of electromagnetic radiation (brightness of light) incident on the surface of a material **does not result in greater E_K** of photoelectrons (demonstrated by V_0 remaining constant), but **does result in more photoelectrons** (greater "photoelectric current").

Frequency greater than f_0 of electromagnetic radiation **does result in greater E_K** of photoelectrons (demonstrated by greater V_0), but **does not result in more photoelectrons** (photoelectric current remains constant).

Quantum Theory And Photons

A "Quantum" is a single, specific amount of energy. "Quanta" is the plural form of "Quantum". A quantum can be considered as small "packet" or "parcel" of energy. Each of these little "packets" or "parcels" can be called a "photon". As long as the PE effect demonstrates light to be constructed from particles, and each of these particles has energy, light can be said to be constructed from photons; so **photons are energy particles, or particles of light**.

As light can also be demonstrated to be a wave, each photon can be thought of as a single cycle, or wavelength of light. Each photon can be thought of as having an oscillating electromagnetic field, which gives it its wave-like characteristics. So light is neither only a particle or a wave, but a wave that can act like a particle, or a particle that can act like a wave.

Photon Energy, Frequency And Planck's Constant

The higher the frequency of electromagnetic radiation, the higher the energy of its photons:

$$E_{photon} \propto f$$

Photon energy and frequency are directly proportional. Planck's Constant is the constant in this relationship:

$$E_{photon} = hf$$

Where E_{photon} = photon energy, in J or eV (depending on the value used for Planck's Constant)
f = frequency of electromagnetic radiation
h = Planck's Constant, $\mathbf{6.63\times10^{-34}Js}$, or $\mathbf{4.14\times10^{-15}eVs}$

In the "wave equation", $v=f\lambda$, v can be replaced with c, the speed of light (the velocity of electromagnetic radiation) to be $c=f\lambda$. This can be re-arranged to be $f=c/\lambda$. c/λ can then be substituted for f into the above formula:

$$E_{photon} = \frac{hc}{\lambda}$$

Where E_{photon} = photon energy, in J or eV (depending on the value used for Planck's Constant)
h = Planck's Constant, $\mathbf{6.63\times10^{-34}Js}$, or $\mathbf{4.14\times10^{-15}eVs}$
c = speed of light, $\mathbf{3.0\times10^{8}ms^{-1}}$
λ = wavelength of electromagnetic radiation, in m

Work Function, W

By definition, "work" is an amount of energy converted or "consumed". The work function, W, for any particular material is the energy required from photons for photoelectron emission to begin. W can therefore be considered as an amount of photon energy that will be absorbed before being converted to E_K of photoelectrons. In this way, W can be thought of as the "threshold energy" corresponding to the threshold frequency (f_0), of any particular material:

$$\text{"}E_{threshold}\text{"} = W = hf_0$$

Where W = work function, in J or eV (depending on the value used for Planck's Constant)
h = Planck's Constant, $\mathbf{6.63\times10^{-34}Js}$, or $\mathbf{4.14\times10^{-15}eVs}$
f_0 = threshold frequency, in Hz

Due to the law of conservation of energy, which states that energy cannot be created or destroyed, only transformed from one kind to another, the sum of W and E_K (energy output) must be equal to E_{photon} (energy input):

$$E_{photon} = E_K + W$$
$$\rightarrow E_K = E_{photon} - W$$

Where W = work function, in J or eV (must be the same as the unit of E_{photon} and E_K)
E_{photon} = photon energy, in J or eV (must be the same as the unit of W and E_K)
E_K = kinetic energy of photoelectrons, in J or eV (must be the same as the unit of W and E_{photon})

The above formula can of course be combined with the formulæ for E_{photon} described previously.

E_K/f Graphs

The relationship between the E_K of photoelectrons and the frequency of incident photons for any particular material can be shown visually as a graph, with E_K on the vertical axis and frequency on the horizontal axis.

- The relationship is always linear with a positive gradient.
- The gradient is always equal to Planck's Constant.
- Where the graph intersects with the (horizontal) frequency axis is always the threshold frequency of the material, f_0.
- Where the graph intersects with the (vertical) E_K axis is always the work function of the material, W, taken as a positive value.

The Compton Effect

If electromagnetic radiation of a particularly high frequency is used to induce the PE effect, not only is the material's work function overcome and photoelectrons ejected, but low energy photons are also emitted. This is the "Compton Effect". Energy of the incident photons is still conserved, so:

$$E_{incident\ photon} = E_K + W + E_{emitted\ photon}$$

Taylor's Experiment

If light's made of particles, it should not diffract like a wave to form interference patterns. Taylor's experiment shows that particles, even if they're only photons, can diffract like waves. This is achieved by enclosing a barrier with a double slit and some photographic paper (to act as a projection screen and record an image) in a completely evacuated and sealed chamber. A light source is filtered through a material of almost negligible transparency, such that only one photon, rather than complete and synchronised wavefronts, can enter the enclosure at a time. Individual photons, one at a time, over a period of many days, pass through the double slits and form an image on the photographic paper very similar to the pattern that would be produced by the interference of diffracted wavefronts, demonstrating that they (the individual photons) do actually diffract.

Photon Momentum

The law of conservation of momentum is such that if photoelectrons have momentum, this momentum must come from the photons which caused their ejection. Photon momentum is given by:

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

Where p = momentum, in $kgms^{-1}$ or Ns
h = Planck's Constant, **6.63×10^{-34}Js**, or **4.14×10^{-15}eVs**
f = frequency of electromagnetic radiation
c = speed of light, **$3.0\times10^{8}ms^{-1}$**

Substituting $f\lambda$ for c, f cancels out, such that:

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

Where p = momentum, in $kgms^{-1}$ or Ns
h = Planck's Constant, **6.63×10^{-34}Js**, or **4.14×10^{-15}eVs**
λ = wavelength of electromagnetic radiation, in m