MODULE 4.5: QUANTUM PHYSICS

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Photons

1. Electromagnetic energy is emitted, transmitted and absorbed in discrete packets or quanta. A quantum of electromagnetic radiation is known as a photon. Photons have no charge – they are neutral.
2. Explain what is meant by a photon?
    a. a quantum of (e-m) energy/light

3. The energy of a photon, E, is proportional to its frequency f, and is expressed as:
    a. $E = hf = \frac{hc}{\lambda}$
    b. Where *E* is the energy of a photon measured in Joules(J)
    c. Where *h* is the Planck Constant: 6.63×10^{-34} Js
    d. Where *f* is the frequency of the electromagnetic radiation measured in Hz
    e. Where *c* is the speed of light in a vacuum: 3.0×10^{8} ms^{-1}
    f. Where λ is the wavelength of the EM radiation in metres (m)

4. $E \propto \frac{1}{\lambda}$
    a. From the above equation we can see the energy of a photon is inversely proportional to its wavelength.
    b. Short-wavelength photons, like X-rays, have much more energy than long-wavelength radio waves.

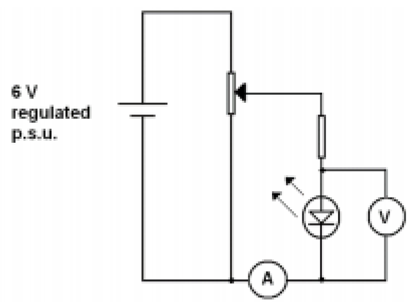
5. A photon of light enters a block of glass after traveling through a vacuum. The energy of the photon on entering the glass block, stays the same because the frequency of the radiation does not change.

6. Photon energies are usually given in electronvolts:
    a. The energies involved when you're talking about photons are so tiny that it makes sense to use a more appropriate unit than the joule.
    b. We often use another unit when measuring energies at the quantum scale, the electronvolt (eV).
    c. **Electronvolt (eV):** the energy of 1 eV is defined as the kinetic energy gained by an electron when it is accelerated through a potential difference of 1V.
    d. Therefore $W = \frac{1}{2}mv^2 = VQ = eV$
    e. As 1 electron volt = $e \times V = 1.6 \times 10^{-19}\,C \times 1\,JC^{-1} = 1.6 \times 10^{-19}\,J$
    f. $1\,eV = 1.6 \times 10^{-19}\,J$

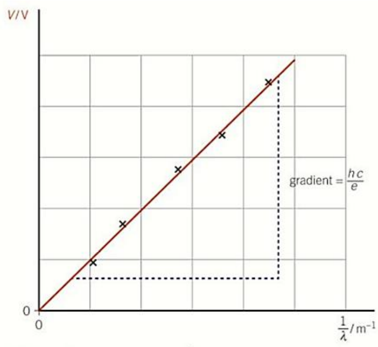
7. How to convert between Joules and electronvolts:
    a. To convert from J to eV, divide by 1.6×10^{-19}
    b. To convert from eV to J, multiply by 1.6×10^{-19}

8. **LEDS and the Planck constant: 6.63 x 10^{-34} Js**
    a. The Planck constant comes up in many aspects of physics. You can finds its value by doing a simple experiment with light-emitting diodes (LED's).
    b. LED's convert electrical energy into light energy. They emit visible photons when the p.d. across them is above a critical value. This is called the threshold voltage, V_0.
    c. When the p.d. reaches V_0 the LED lights up and starts emitting photons of a specific wavelength.
    d. At this V_0 the work done is given by W = VQ
    e. The energy of an electron equals the energy of the (emitted) photon.
    f. Therefore $E = eV_0 = h\frac{c}{\lambda}$
    g. Rearranging the above for Planck's constant gives $h = \frac{(eV_0)\lambda}{c}$
    h. So by finding the threshold voltage for a particular wavelength LED, you can estimate the Planck constant. We can use a voltmeter to measure the threshold voltage. A black tube places over the LED helps to show exactly when the LED lights up.

9. Describe the experiment used to estimate the Planck constant.
    a. In order to obtain an accurate value for the Planck constant, we will use a number of different monochromatic LED's. The threshold voltage dictates the colour of the LED.
    b. Describe the experiment:
        i. The wavelength λ of the emitted photons is determined during the manufacturing process.
        ii. Adjust the potential divider to zero voltage.
        iii. Place the first LED into the circuit as drawn, and record its wavelength.
        iv. Increase voltage until LED just lights/strikes. Shield the LED inside an opaque tube to judge strike more accurately.
        v. Repeat 3 times and average to find V_0. Record the average minimum voltage.
        vi. Repeat for each colour LED.



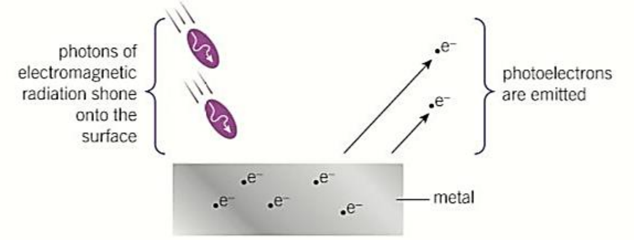
    c. How to calculate the Planck constant:
        i. With your results, plot a graph of threshold voltages (V_0) against 1/ λ (where λ is the wavelength of light emitted by the LED in metres).
        ii. After plotting your results, draw the line of best fit. It should be a straight line that passes through the origin.
        iii. As the graph shows a line with equation y=mx +c, and the y axis = V_0 , x axis = 1/ λ , and c (the y intercept) is zero, the gradient of the line = $V_0\lambda$
        iv. As V_0 and λ are related by the equation: $eV_0 = h\frac{c}{\lambda}$, rearranging for h gives $h = \frac{e(V_0\lambda)}{c}$.
        v. Therefore, the Planck constant is the gradient multiplied by e/c
            1. h = (Vλ) x (e/c)



▲ Figure 4 A plot of V against $\frac{1}{\lambda}$

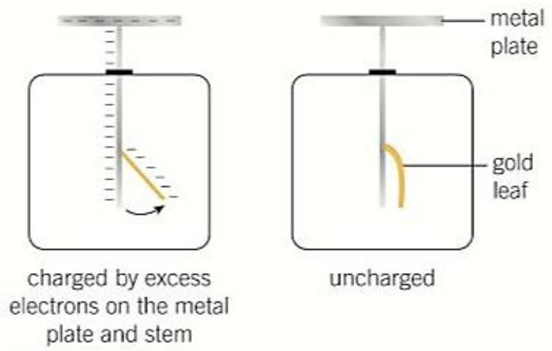
The photoelectric effect

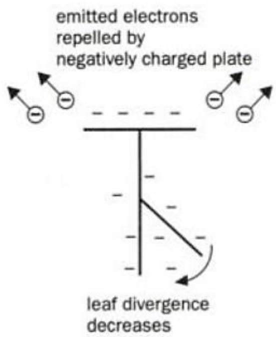
1. **The photoelectric effect:** emission of electron(s) from a metal (surface) when EM radiation is incident on the surface.
    a. The emitted electrons are sometimes called photoelectrons. They are normal electrons, but their name describe their origin – emitted through the photoelectric effect.



▲ **Figure 2** *The photoelectric effect occurs when electromagnetic radiation incident on the surface of a metal causes electrons to be emitted*

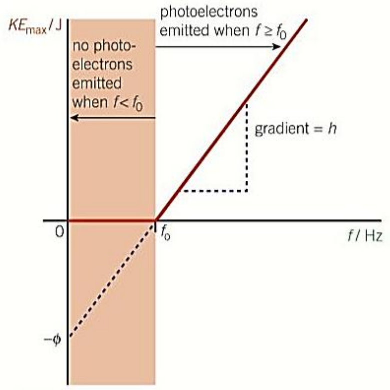
2. Describe an experiment to demonstrate the photoelectric effect. Describe how you would use the apparatus and what would be observed.
    a. The electroscope plate is initially negatively charged. Both the stem and the gold leaf have the same charge, they repel each other, and the leaf lifts away from the stem.
    b. A clean zinc plate is then mounted on the cap of a gold-leaf electroscope.
    c. shine UV lamp on plate
    d. Whilst UV light is incident on zinc plate gold leaf collapses as the charge leaks away from the plate.
    e. This shows that the electroscope has gradually lost its negative charge, because the incident UV radiation has caused free electrons to be emitted from the zinc.
    f. If the electroscope is initially positively charged, the gold leaf does not move from its raised position: no effect is observed. This occurs as any emitted electrons are immediately attracted back to the plate as 'unlike charges attract'. So photoemission does occur, but the electroscope does not discharge.
    g. When a glass sheet (which absorbs UV) is placed between the lamp and the zinc, the gold leaf does not collapse, showing that it is the UV which is causing the discharge.





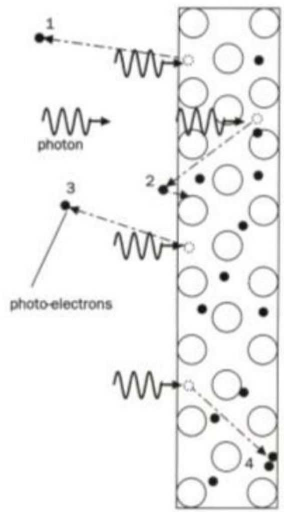
3. Threshold Frequency and Work function:
    a. **Threshold frequency, f_0:** The Threshold frequency (for a particular metal) is defined as the minimum frequency of incident light which can cause photo electric emission.
    b. **Work Function, ϕ**: the minimum energy required to release an electron from the surface (of the metal).
    c. A photon with less than the threshold frequency f_0 cannot cause electron emission so $\boldsymbol{\phi} = \mathbf{hf_0}$

2. Photoelectric Equation:
    a. When a photon hits a surface electron it has a one-to-one interaction.
    b. The photons either transfer all or none if its energy when interacting with an electron. Energy is conserved.
    c. The energy (E) transferred to an electron is *hf*
    d. The kinetic energy it will be carrying when it leaves will be *hf* minus any energy it's lost on the way out. Therefore emitted electrons have a range of energies.
    e. The minimum amount of energy an electron can lose is the work function energy, so the maximum kinetic energy is given by Einstein's photoelectric equation:
        i. $E = hf = \varphi + KE_{max}$
        ii. Where $KE_{max} = \frac{1}{2}mv_{max}{}^2$ and $\varphi = \mathrm{h}f_0$
    f. Einstein's equation can be rearranged to $KE_{max} = hf - \varphi$
        i. This is in the same format as y = mx + c. so if you plot a graph of KE_{max} against *f* for a specific metal, the gradient of the line would be *h* and the y-intercept would be the negative of the work function of the metal, $-\varphi$. The gradient will always be *h*, the Planck constant for any metal.



▲ **Figure 2** *A graph to show how the frequency f of the incident radiation on a metal surface affects the maximum kinetic energy KE of the emitted photoelectrons*

3. Why is the kinetic energy of a maximum value in Einstein's equation:
    a. Electrons in the metal are situated in different parts of the metal lattice. Those near the surface, surface electrons, do not lose any kinetic energy upon escape unlike those within the lattice. Therefore it is KE_{max}. Non-surface electrons are slightly deeper within the metal than surface electrons and so escape with slightly less kinetic energy as they require slightly more energy than the work function energy to escape.
    b. If a photon strikes the surface of the metal with the work function energy, then it will only have enough energy to free a surface electron, with none left over to be transferred into kinetic energy of the electron. In this case Einstein's equation become $E = \varphi = \mathrm{h}f_0$



4. The photoelectric effect – observations and explanations:

What is observed?	What does the Wave Theory predict?	What does the Particle Theory predict?
For a given metal, electrons are only emitted above a certain threshold frequency of the EM radiation, irrespective of its intensity.	For a particular frequency of EM radiation, the energy carried is proportional to the intensity (amplitude^2) of the beam. So a high enough intensity should cause electrons to be emitted regardless of the frequency. The frequency should have no effect here.	Light consists of photons with energy E = hf The minimum energy required to release an electron is the work function (**ϕ**) To release electrons, E> **ϕ** Threshold frequency (f0) occurs when E= **ϕ**; $hf_0 = \phi$
The photoelectrons are emitted with a variety of kinetic energies ranging from zero to some maximum value. The maximum KE of the emitted electrons depends only on frequency of the EM radiation and is unaffected by the intensity of the radiation.	In the wave model, increasing the intensity delivers more energy to all electrons so the wave model would expect the electrons to be released with more K.E.	KEmax = hf – Φ The maximum kinetic energy of the emitted photoelectrons depends only on the energy of incident photons and the work function energy of the metal. It is independent of intensity as it is a one to one interaction. Increasing the frequency of the incident light will increase KEmax
The number of photoelectrons emitted per second depends only on intensity of the EM radiation, for a single frequency	The intensity of the EM radiation relates to energy, not the number of waves arriving per second. So, the number of emitted electrons depends on the number of waves arriving (i.e. the frequency) and not the wave energy (i.e. intensity). The intensity should have no effect here.	The number of photoelectrons emitted above the threshold frequency is directly proportional to the intensity of the incident radiation. Intensity is proportional to number of photons incident on surface per second. One photon can release one electron (assuming 100% efficiency) Thus the number of electrons emitted per second depends on intensity and not the frequency.
Low intensity EM radiation (above the threshold frequency) results in immediate emission of electrons.	Low intensity EM radiation has low energy. So it will take some time before enough energy builds up on the metal surface to free one electron	Intensity only relates to how many photons arrive per second, so few arrive per second for low intensities But, each photon has enough energy to release an electron ($f>f_0$) so immediate electron emission occurs. Also, as it is a one-to-one interaction, electrons cannot accumulate the energy.

5. **Describe how the photoelectric effect can be explained in terms for the physics of quantum behaviour:**
    a. Individual photons are absorbed by individual electrons in the metal surface
    b. only photons with energies above the work function energy will cause emission of an electron from the surface
    c. Energy is conserved in the interaction
    d. emission of photoelectron is instantaneous
    e. rate at which electrons are emitted depends on light intensity
    f. the energy of the photo electron is given by Einstein's photoelectric equation
        i. $E = \Phi + KE_{max}$
        ii. E = energy of photoelectron
        iii. Φ = work function energy of metal
        iv. KE_{max} = maximum possible kinetic energy of emitted photoelectron

6. Use the particle theory of light to explain why red light does not have the same effect as ultra-violet light:
    a. Light consists of packets (quanta) called photons
    b. The energy of each photon depends on its frequency, by $E = hf$
    c. As red light has a lower frequency than UV light, it has less energy.
    d. One photon gives its energy to one electron.
    e. In order to release an electron, the photon energy must be greater than or equal to the metal work function:
    f. Red light photons have less energy than this and so do not provide enough energy to free an electron.
    g. Therefore, it only causes the surface to heat up

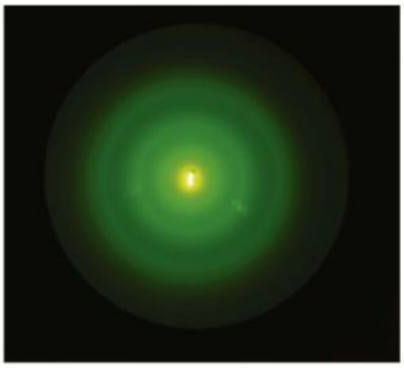
Wave–particle duality:

1. Electromagnetic radiation can show characteristics of both particles and waves.
2. Light produces interference patterns and diffraction patterns – alternating fringes of dark and light.
3. These can only be explained using waves interfering destructively or interfering destructively.
4. The photoelectric effect provides evidence for particulate nature of electromagnetic radiation.

5. The De Broglie Wave Equation
    a. Louis de Broglie made a bold suggestion in his PhD thesis: If 'wave-like' light showed particle properties (photons), 'particles' like electrons should be expected to show wave-like properties.
    b. The de Broglie equation relates a wave property (wavelength, λ) to a moving particle property (momentum, p, in $kgms^{-1}$). *h* is the Planck constant = 6.63×10^{-34} Js
    c. $\lambda = \frac{h}{p} = \frac{h}{mv}$

6. Explain what is meant by the de Broglie wavelength of an electron.
    a. Electrons are observed to behave as waves/show wavelike properties
    b. Where an electrons wavelength depends on its speed/momentum.

7. **Electron diffraction:** observations
    a. Diffraction patterns are observed when accelerated electrons in a vacuum tube interact with the spaces in polycrystalline graphite.
    b. This confirms electrons show wave-like behaviour
    c. The spread of the lines increases if the wavelength is greater according to wave theory
    d. In electron diffraction experiments, a smaller accelerating voltage i.e. slower electrons gives widely spaced rings.
    e. Increase the electron speed and the diffraction pattern circles squash together towards the middle. This fits with the de Broglie equation – if the velocity is greater, the wavelength is smaller and so spread of the lines is smaller as less diffraction occurs.

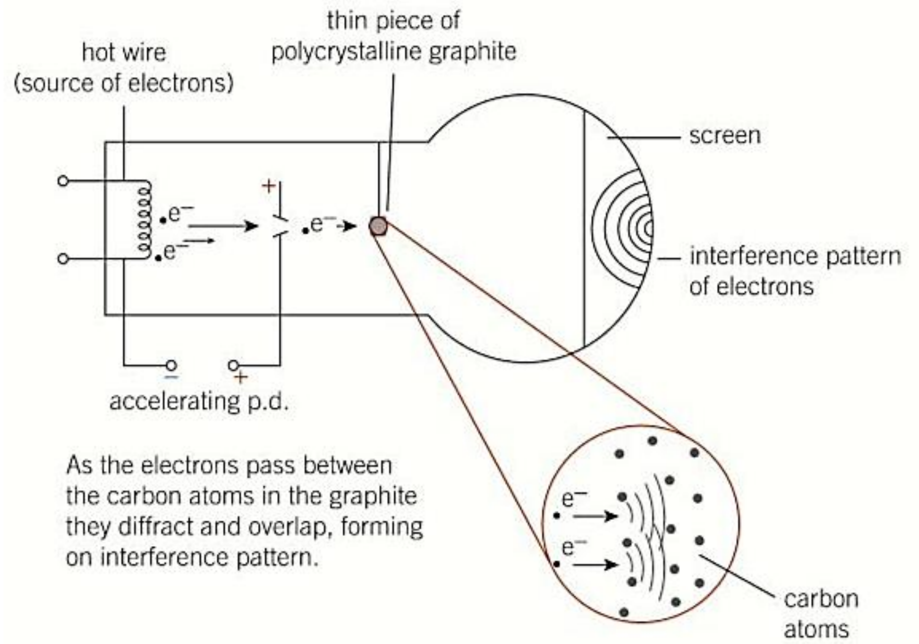


▲ **Figure 3** *These rings are the result of the diffraction of electrons*

8. Explain why a beam of electrons passing through a thin sheet of graphite in a vacuum produces a pattern of rings on a fluorescent sheet placed after the graphite
    a. Electrons behave as waves and have a wavelength.
    b. The regular pattern of atoms acts as a diffraction grating.
    c. diffraction observable because gaps between atoms are similar to wavelength of electrons
    d. maximum intensity when constructive interference, path difference = nλ
    e. minimum intensity when destructive interference
    f. rings occur because atomic 'crystals' at all possible orientations to beam

9. Both electrons and photons can be considered as particles. State two differences between their properties.
    a. electrons have mass, photons have zero mass electrons have charge, photons are uncharged and photons travel at speed of light

10. Electron diffraction set-up:



11. State one experiment for each case which provides evidence that electromagnetic radiation can behave like,
    a. a stream of particles, called photons:
        i. photoelectric effect (experiment)
    b. waves:
        i. Young's slits (experiment)

12. State one experiment for each case which provides evidence that particles can behave like waves:
    a. Electron gun and polycrystalline graphite experiment

13. All objects have a de Broglie wavelength. But for diffraction patterns to occur, gaps have to be of a similar size to the wavelength of the particle. Ordinary day objects have extremely small de Broglie wavelengths and so we don't observe their diffraction.

14. State the condition necessary for electrons to produce observable diffraction when passing through matter, e.g. a thin sheet of graphite in an evacuated chamber.
    h. wavelength of electrons
    i. must be comparable to the atomic spacing

15. A shorter wavelength gives less diffraction effects. This fact is used in the electron microscope. Diffraction effects blur detail on an image. If you want to resolve tiny detail in an image, you need a shorter wavelength. Light blurs out detail more than 'electron-waves' do, so an electron microscope can resolve finer detail than a light microscope.