2 Photons as particles

By the turn of the 20th century the laws of physics were based on mechanics (newton), gravitation (newton), electricity and magnetism (Maxwell) and thermodynamics/statistical physics

these described almost all known phenomena in physics under the conditions known at that point. But there were a few peculiarities, and the list of these 'exceptions' started to grow.... out of this came two major new braches of physics - relativity (special, followed by general) and quantum mechanics.

In classical physics, matter is collections of particles moving under newtons law of Notion. Motion is predetermined by the momentum and positions of all the particles of interest. If we know all these at some point, we can predict all the future behaviour.

photons - electromagnetic radiation: obey Maxwell equations formed from 4 empirical laws

1) Coulombs law - force between charged particles

2) Biot-Savoit law - force between two currents

3) Faradays law of induction - changing magnetic flux induces an electromotive force

4) Ampere-Maxwell law - changing electric flux causes a magnetic field

taken together these give us Maxwells equations which describe electromagnetic fields propagating through the vacuum as waves with speed c.

$$\frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t} = \frac{\partial^2 \vec{E}}{\partial^2 x}$$

and

$$\frac{1}{c^2}\frac{\partial^2 \vec{B}}{\partial t} = \frac{\partial^2 \vec{B}}{\partial^2 x}$$

so what were the bits that didn't fit ? some of them just seemed like 'details'

why does sodium vapour emit yellow light?

what sets the chemical properties of hydrogen?

how does the sun shine for such a long time - age of earth already known to be old but if the sun is powered by chemical burning then it should have run out of fuel....

why does uranium disintegrates?

why do metals conduct electricity

and the photo-electric effect, described in more detail below

2.1 Photo-electric effect

when light shines on electrons in a metal, electrons can be ejected. We'd expect this from the wave nature of light - waves carry energy and we can imagine that electrons can be ejected from a surface if we given them enough energy.

But first, we 'know' photons are waves which travel in a vacuum at c. so then we can predict what we should see.

the intensity of a wave depends on its amplitude squared not its frequency. so photo-electric effect can happen for light of any frequency.

it will take some mimium amount of energy to eject an electron from a surface, so it should take some time to accumulate enough energy from the wave for very dim light.

whereas for very bright light then the electrons will leave with a lot of KE

so experimental setup - get light to shine on a metal, put a voltage across, and get a current. put it all in a vacuum to minimise collisions with air, to measure how many electrons by measuing current, measure their energy by changing the voltage. the electrons can't make it to the anode if we change the voltage below $-V_0$ where $eV_0 = KE$. This is called the stopping potential.

Experiment: current only starts when illuminate with light of frequency $f > f_{crit}$. There is more current when we increase the intensity but only if we have $f > f_{crit}$.

there is no time delay for very dim light.

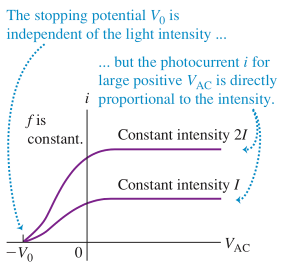
the maximum KE of the emitted electrons depends on frequency, not on intensity.

this is NOT AT ALL WHAT was predicted from the wave nature of light!!!

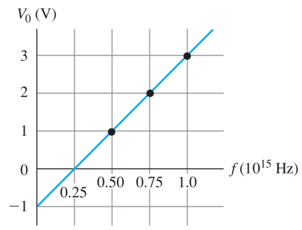
Einstein EM waves have energy concentrated in 'bundles' now called photons having energy $E = hf = hc/\lambda$. A single photon can hit an electron and knock it out ONLY if it has enough energy. repeatedly doing this (higher light intensity) with lower energy photons won't work. Its an extension of an idea developed 5 years earlier by Plank to explain blackbody radiation. it incorporates $h = 6.63 \times 10^{-34}$ Js.

This minimum energy require to eject an electron is different for each material - called the work function ϕ. If $hf < \phi$ then no electrons are emitted. The KE of the emitted electron is whatever is left after the work function so $KE = hf - \phi$ but we measured this using the stopping potential

38.4 Photocurrent i for a constant light frequency f as a function of the potential V_{AC} of the anode with respect to the cathode.



38.5 Stopping potential as a function of frequency for a particular cathode material.



so $hf - \phi = eV_0$. The stopping potential (electron KE) increases linearly with f but ONLY after $hf = \phi$.

Example: light $\lambda = 300$ nm is incident on potassium. it emitts electrons with a maximum KE of 2.03 eV

i) what is the energy of the photon?

$E = hf = hc/\lambda = 6.626 \times 10^{-34} \times 3 \times 10^8/300 \times 10^{-9} = 6.63 \times 10^{-19}$ J

1eV= 1.602×10^{-19} J so this is 4.13eV.

ii) what is the work function of the metal?

we were given KE is 2.03eV, and KE=$hf - \phi$ so $\phi = 4.13 - 2.03 = 2.1$ eV

iii) what is the maximum KE of the emitted electrons if the light has $\lambda = 430$ nm?

can do from $E = hc/\lambda$ OR ratio $E_1/E_2 = \lambda_2/\lambda_1$ so

$E(430) = E(300) * 300/430 = 4.13 * 300/430 = 2.88$ eV

then $KE = hf - \phi = 2.88 - 2.1 = 0.78$ eV

iv) what is the threshold wavelength for the photoelectric effect in potassium?

$hc/\lambda = \phi = 2.1$ eV so $\lambda = 6.626 \times 10^{-34} 3 \times 10^8/(2.1 \times 1.602 \times 10^{-19} = 5.91 \times 10^{-7}$ m so 591nm.

2.2 X-ray emission

Light really is absorbed as individual 'photons' in the photo-electric effect rather than being supplied continuous energy via a wave. so is it also EMIT-

TED as individual 'photons'? We see that the answer to this is 'yes' when we look at X-rays. heat the cathode to high tempertures, so it gives off electrons. accelerate towards the anode by a very high voltage V to accelerate them (so the initial KE of electrons is negligible in comparison to what they gain!). so the electrons have LOTS of KE= eV. They smash into the anode and decelerate - Charges (de)celerating emit 'bremsstrahlung' (braking radiation) rapidly in a sequence of collisions with atoms in the anode - continuum spectrum at X-ray energies.

wave model predicts that em waves at all frequencies should be produced like sound waves from smashing cymbols together!

we do see a continuum, but it does NOT extend over all frequencies. there is a maximum frequency (or minimum wavelength) which is present. This max frequency increases as the accelerating voltage increases (or min wavelength decreases as V increases)

we can understand this if light is also emitted as photons of energy hf. Then $KE_{max} = eV = hf_{max} = hc/\lambda$ and there is a maximum photon energy corresponding to the maxium electron KE.

Example: electrons accelerated through potential of 10kV before striking target. what is the minimum wavelenght of the X-ray produced?

$E = hc/\lambda = 10 \times 10^3 = 10^4$ eV

$\lambda = 1240/10^4 = 0.124$nm

38.8 The continuous spectrum of x rays produced when a tungsten target is struck by electrons accelerated through a voltage V_{AC}. The curves represent different values of V_{AC}; points *a*, *b*, *c*, and *d* show the minimum wavelength for each voltage.