1 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 Motion, $\vec{F} = m\vec{a}$. 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 - this gives us all of classical mechanics. Electromagnetic radiation is a wave propagating through the vacuum with speed c, obeying Maxwells equations- this gives us all of electromagnetism!

So what were the bits that didn't fit ? One of them was the photo-electric effect.

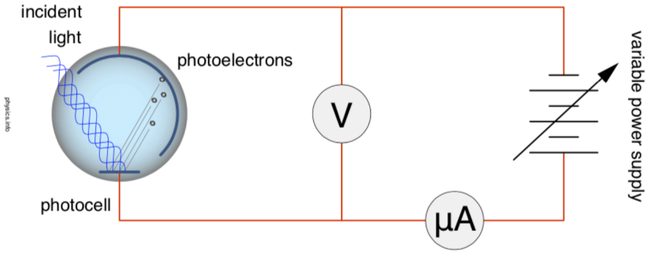
1.1 Photo-electric effect

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 give them enough energy. So then we can predict what we should see, given that there will be some minimum energy to eject an electron from the surface as its bound to ions (binding energy, called work function ϕ which will depend on the specific material)

the energy of wave proportional to amplitude squared, so as long as the amplitude is high enough for a single peak to eject an electron then

1) the current (number per second ejected) depends on frequency of the wave



2) the KE of the ejected electrons depends on intenisty (amplitude squared) - binding energy

if instead the amplitude isn't high enough to overcome the binding energy, then it should take some time to accumulate enough energy from the wave. So for very dim light there should be a time delay between the first photons hitting the metal and the photo-electrons being ejected

The experimental setup is simply get light to shine on a metal, put a voltage V across, and get a current. put it all in a vacuum to minimise collisions with air, and measure the current.

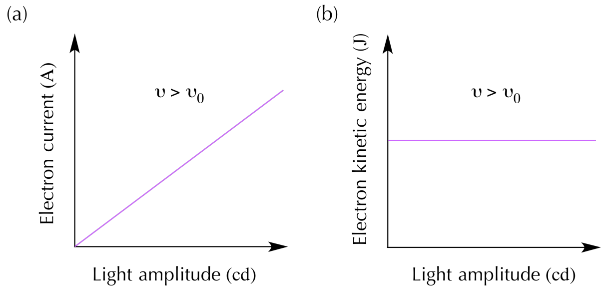
The KE can then be measured energy by changing the voltage. the electrons can't make it to the anode if we change the voltage below $-V_0$ where $eV_0 = KE$. This is called the stopping potential - its the voltage we apply to stop the electrons reaching the electrode.

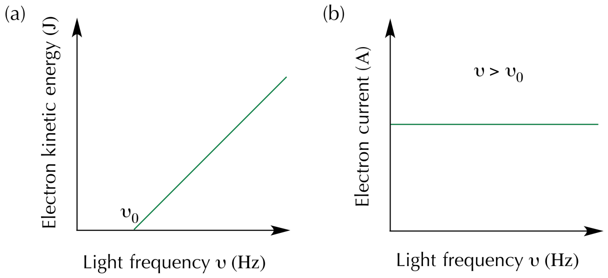
summary: light as waves predicts:

current depends on frequency not amplitude

KE depends on amplitude not frequency

time delay for very dim light





Experimental results:

current depends on amplitude not frequency

KE depends on frequency not amplitude

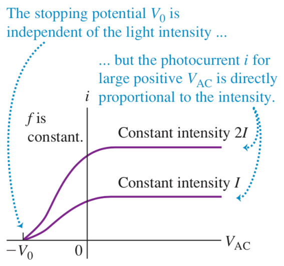
there is no time delay for very dim light.

The current only starts when illuminate with light with frequency larger than some critical frequency f_{crit}. There is more current when we increase the intensity but only if we have $f > f_{crit}$. The current starts with no time delay for $f > f_{crit}$ but never starts for $f < f_{crit}$

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 $E = hf = hc/\lambda$ where $h = 6.63 \times 10^{-34}$ Js. 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.

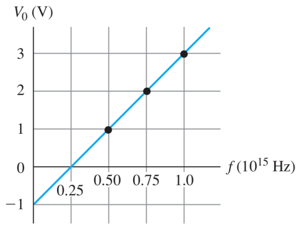
If $hf < \phi$ then no electrons are emitted. The KE of the emitted electron is whatever is left after the work function so $KE = hf - \phi$ but we measured this using the stopping potential so $hf - \phi = eV_0$. The stopping potential



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.

The stopping potential V_0 is independent of the light intensity ...

... but the photocurrent i for large positive V_{AC} is directly proportional to the intensity.



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

(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$= 1.602 \times 10^{-19}$ 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.

we've been using $hc = 6.6 \times 10^{-34} \times 3 \times 10^8$ J m but often we'll have wavelengths in nm no m, and energies in eV not J

so we can convert the constant $hc = 1240$ eV nm and everything is more managable. $\lambda_{max} = 1240/\phi(eV) = 1240/2.1 = 591$ nm

1.2 X-ray emission

In Einstein's picture, 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 EMITTED 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.

The wave model predicts that em waves at all frequencies should be produced like sound waves from smashing cymbols together! Some frequencies have higher amplitude (harmonics) but they are all present.

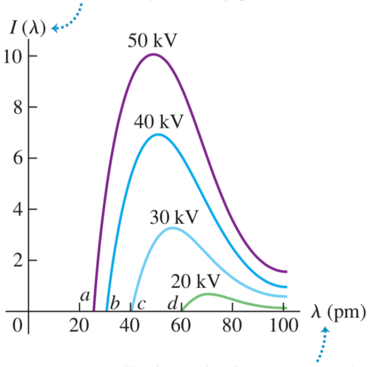
We do see a continuum, but it does NOT extend over all frequencies. there is a maximum frequency (or minimum wavelength) which is present. This max frequency increases as the accelerating voltage increases (or min wavelength decreases as V increases)

we can understand this if light is also **emitted** in separate bits 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 wavelength of the X-ray produced?

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.

Vertical axis: x-ray intensity per unit wavelength



Horizontal axis: x-ray wavelength in picometers (1 pm = 10^{-12} m)

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

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

1.3 Photon momentum

Electro-magnetic waves have no mass. We've just seen that they come in 'bits' of energy called photons. But a bit of nothing is still nothing so photons have no mass either. Hence if we are considering this as a classical particle then they can't have momentum as $p = mv$. However, classical waves do carry momentum, which relates to the wave energy by $p = E/v$ where v is the group velocity of the wave. So for EM waves which travel at c then this gives $p = E/c$ (we'll see this is correct in relativity in a few weeks time, and sorry I got this upside down in the lecture!). Hence we get that each photon has momentum $p = E/c = hf/c = h/\lambda$.

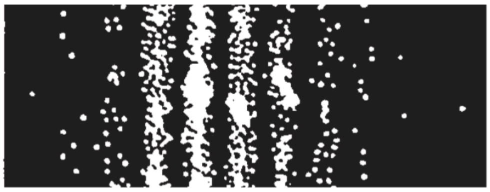
1.4 Wave-particle duality

So electromagnetic waves can look like particles (photons)

38.16 These images record the positions where individual photons in a two-slit interference experiment strike the screen. As more photons reach the screen, a recognizable interference pattern appears.

After 21 photons reach the screen

After 1000 photons reach the screen



After 10,000 photons reach the screen

but they do also look like waves - we saw they did interference patterns in youngs double slit experiment.

lets turn down the intensity of the beam so that only 1 photon on average goes through at any one time. then it will have to pick only one slit, and we'll just see the 2 slit pattern on the screen, not the full interference pattern....but thats not what is seen! we do indeed see individual photons. Experimentally, there is no way to predict exactly where any individual photon will land. But after a while we accumulate enough photons to see the full interference pattern that we expect from waves. We see that the probability of detecting a photon at any point is given by the intensity of the expected wave interference pattern.

There is no classical description that works - we can't have just classical particles (photons) to explain photoelectric effect as we know that EM waves do interference/diffraction as a wave. And besides, classical particle have well defined position and so we should be able to explain where they go. But similarly, we can't just have classical waves (to explain interference/diffraction) as they come in bits as detected in the photo-electric effect and on the screen. We somehow need both. This is wave-particle duality.