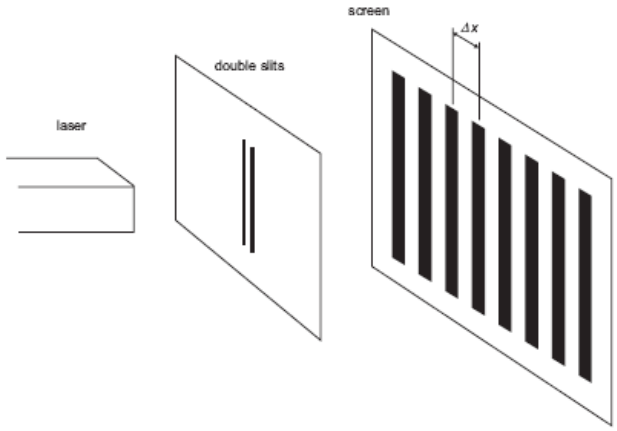
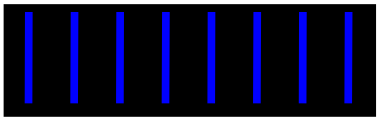
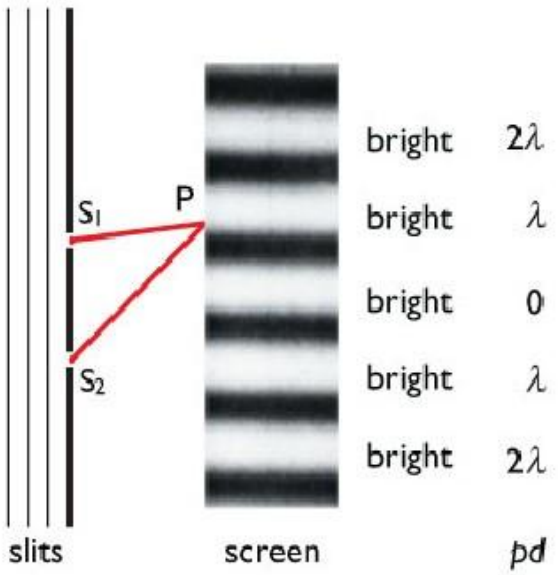
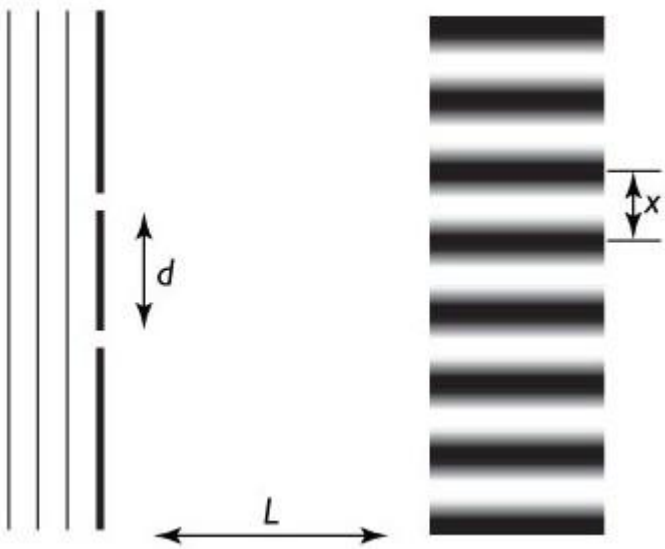
Light-Matter

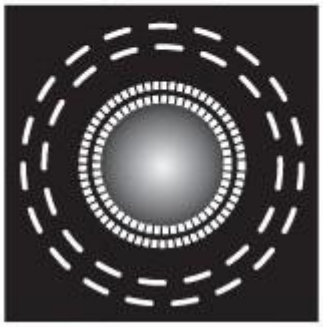
What was Young experiment all about?	This experiment demonstrated that light behaves as a wave. Essentially Thomas Young passed a light of a single frequency (colour) through a pair of closely spaced narrow slits and on the screen and interference pattern was produced. This pattern has a series of equally spaced coloured and black bands. The width of the coloured bands and their spacing apart depends on the wavelength of light used. Below is a picture of the experiement  Figure 4 This experiment provided convincing evidence for the wave-like nature of light as only waves cancel or add each other by interference A particle like model for light would predict just two bright fringes, each fringe opposite one of the slits.
What happens when different colours of light is used?	Red light- longer wavelength, produces a pattern with a wider red bands which are spread further apart RED Blue light – shorter wavelength produces a pattern with narrow blue bands which are closely spaced  BLUE
What is the relationship between wavelength and interference produced?	Remember monochromatic light of wavelength λ falls on two narrow slits S_1 and S_2 Each slit acts as a source of coherent circular waves On the screen the two waves produce an interference pattern of bright and dark fringes. At the central maximum the two waves have travelled the same distance. So the path difference (PD) is $PD = S_2P - S_1P = 0$ Now the central waves constructively interfere and produce a bright fringe.

	For Bright bands to occur the PATH DIFFERENCE , $PD = n\lambda$, where $n = 0,1,2,3,4$ For Dark bands to occur the PATH DIFFERENCE, $PD = (n - \frac{1}{2})\lambda$ Where $n = 1,2,3,4$ 
General Behaviour of the fringes and the width of the fringes	 Not the fringes are equally spaced The experiment shows that the fringe spacing, x -increase as the wavelength λ increases -increases as the distance to the screen L increases -decreases as the slit separation, d, increases A formula that determines the fringe spacing $x = \frac{\lambda L}{d}$

De Broglie's matter wave postulate Wavelike nature of matter	Any particle of matter of mass, m, moving with velocity v (and hence momentum p= mv) has an associated wavelength given by $\lambda = \frac{h}{p} = \frac{h}{mv}$ Example: A ball of mass 0.2 kg is moving with a speed of 20 m/s has a wavelength according to the above formula of $\lambda = \frac{h}{mv} = \frac{6.63\times10^{-34}}{0.2\times20} = 1.66\times10^{-34}$, which is smaller than an atom. The wavelike properties of everyday properties cannot be observed. But when objects are travelling at faster speeds things are different. Take an electron of mass 9.11×10^{-31} and having a speed of 5×10^{6} $\lambda = \frac{h}{mv} = \frac{6.63\times10^{-34}}{9.11\times10^{-31}\times5\times10^{6}} = 1.46\times10^{-10}$, This is still very small but it is comparable to the spacing of atoms in a crystal. Waves of matter of wavelength it does not have a frequency.
Diffraction of light	 All waves diffract or spread out when they pass through a slit which is comparable to their wavelength. When light waves pass through a slit whose width, w, is the same order of magnitude as the wavelength we observe the following: -light starts to diffract or spread out -a diffraction pattern is set up with a broad central maximum and a series of bright and dark fringes. The spacing of the fringes is proportional to the ratio $\frac{\lambda}{w}$ so that - As the wavelength increases the pattern spread out - As the slit width increases the pattern contracts Light waves passing around the obstacle will show similar diffraction if the ratio $\frac{\lambda}{w}$ is comparable to 1
Diffraction of electrons	In one experiment a beam of electrons is scattered from the surface of a single crystal. The electrons are reflected strongly at several different anges. The pattern is due to electron waves diffracting from different layers of atoms and constructively interfering at certain angles. In a different experiment a beam of X-rays is first passed through a thin powdered metal foil. The x-rays diffract from the random atomic layers and produce a diffraction pattern with circular rings. Next a beam of electrons with a de Broglie wavelength equal to the wavelength of the x-rays is also passed through the same target. The electrons produce a diffraction pattern of the same shape and size as the x-rays thus showing the same wave

nature.

(a) X-ray



(b) electrons

Both photons and material particles like electrons have their wavelengths determined by their momentum- $p = \frac{h}{\lambda}$

So a photon and a electron with the same wavelength must have the same momentum. But they will have very different speeds or energies

Photons

-photons have zero mass and a fixed speed of c

- their energy is given by the following equation $E = \frac{hc}{\lambda}$

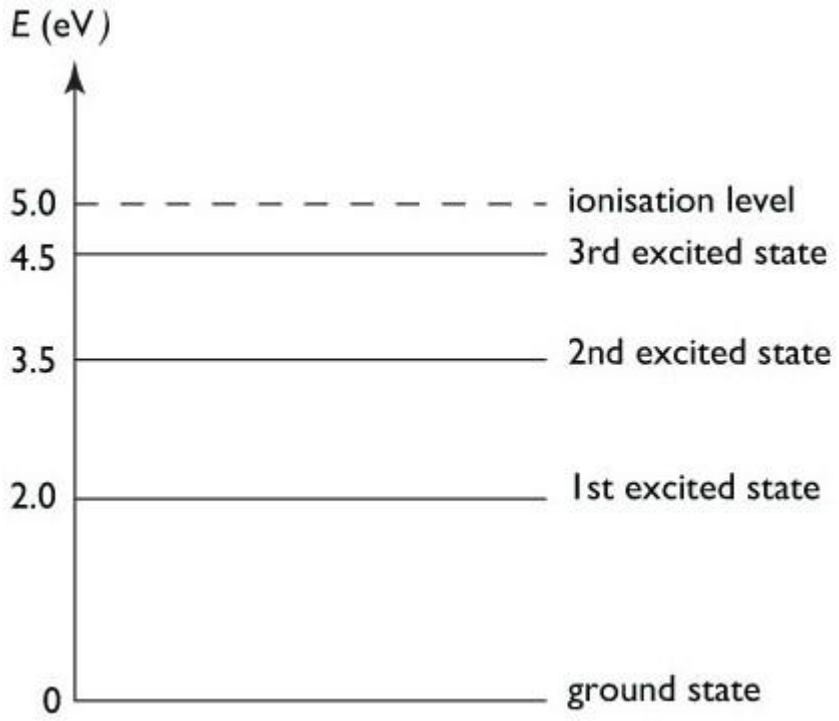
Material Particles (such as electrons)

- Material particles have a mass of m and varying speeds given by formula $v = \frac{p}{m}$
- The kinetic energy is given by $E_k = \frac{1}{2}mv^2$

Both photons and particles will show diffraction effects when they are scattered from crystals with atomic spacing- d, comparable to their wavelength, λ

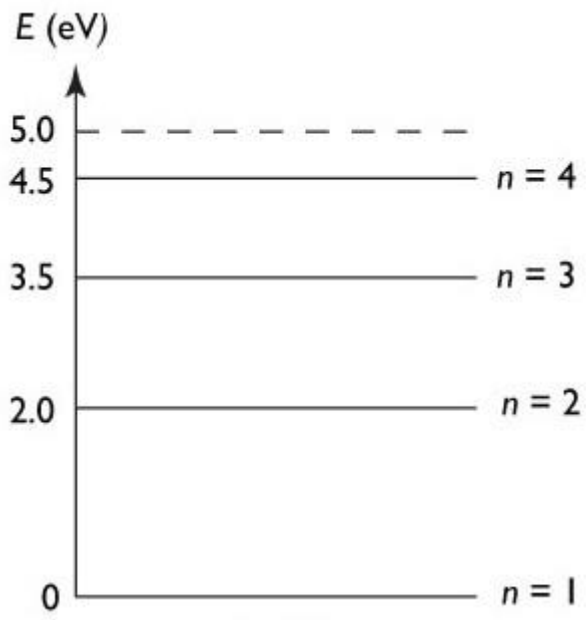
Atomic spectra and structure -Emission spectra	The spectrum of light from an incandescent source is continuous- meaning the colour change smoothly from one to another with no boundaries or gaps But light from excited atoms such as in a metal vapour lamp produces a line emission spectrum. This has a set of discrete bright spectral lines each of a specific wavelength and frequency and a specific photon energy The energy of photon given off is given by the following equation $E_{photon} = \frac{hc}{\lambda}$ Each element emits a unique line of emission spectrum thus each element emits a unique set of photon energies.
Atomic spectra and structure- Absorption spectra	If white light is passed through a cool gas and then analyzed it produces a continuous spectrum crossed by a series of dark lines. This is called a line of absorption spectrum. The dark lines represent frequencies of light that have been absorbed by atoms of each element present in the gas. The line absorption spectrum is unique to each element. Each frequency of light absorbed by a particular element matches **exactly** with one of the frequencies of light emitted by that element. This means that atoms of an element are only able to absorb photons with energies **exactly** equal to those of photons that can be emitted by atoms of that element.
Quantised energy level model of the atom	An atom normally exists in its lowest energy level which we call the ground state An atom can also exist in a number of higher energy levels (if it is excited), each with a specific energy level value Rules 1. An atom cannot exist in any state with energy between these allowed values 2. The energy states are said to be quantized A particular set of energy levels is unique to each element.

Energy Level diagram for a element

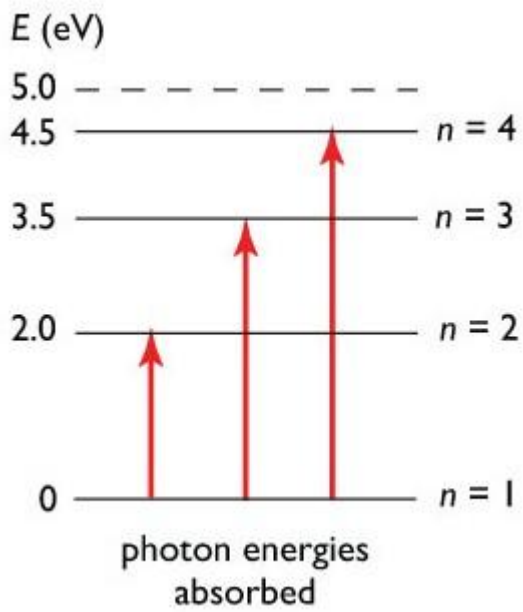


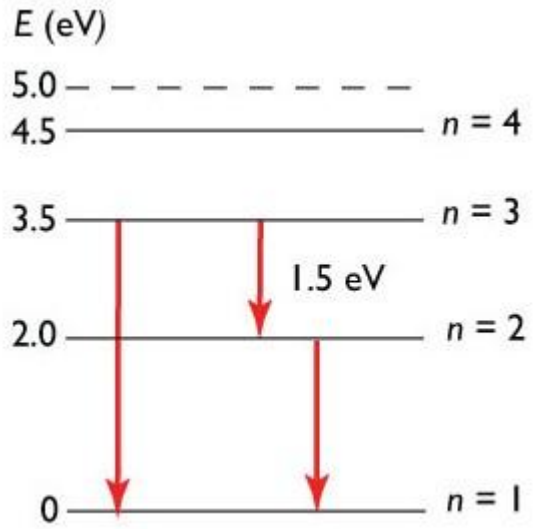
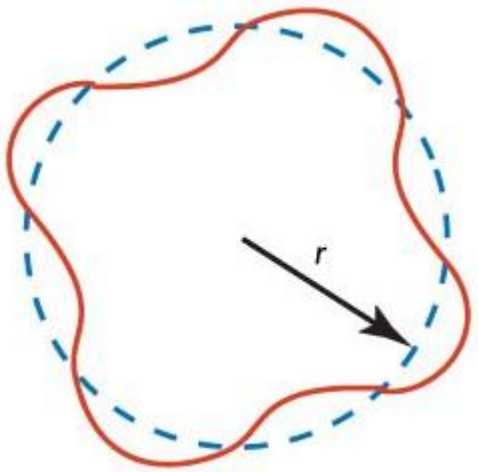
To escape this atom an electron will need to receive the ionization energy of 5 eV

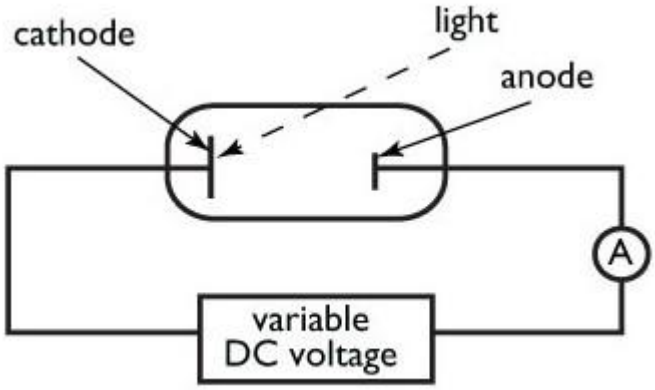
The energy level diagram can be shown in many different ways- either showing positive values in Y-axis or negative values in Y-axis

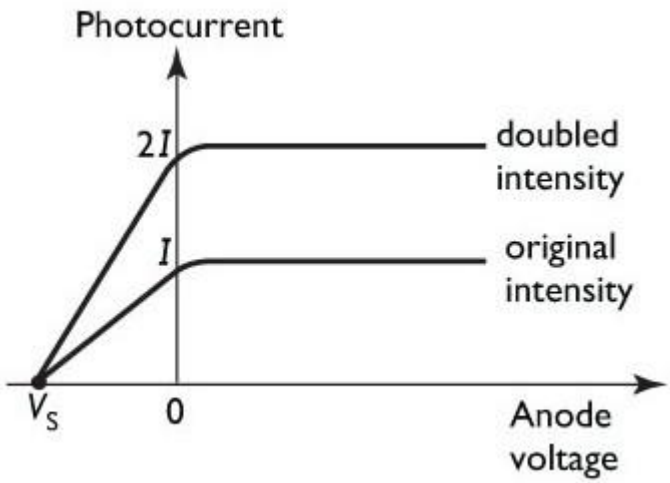


The energy levels can be described by their n-values where
$n = 1$ is the ground state
$n = 2$ is the first excited state etc

	RULES 1. An atom can only absorb energy in exactly the amounts that will raise it from one state to a higher energy state 2. An atom can absorb any amount of energy greater than its ionization energy because an electron is ejected from the atom. 3. Once excited the atom will get rid of its excess energy by dropping down to a lower energy level. The energy difference between the levels will be given off as a photon with that energy.
Example	Example  Atoms are normally in their ground state The atom above can absorb photons with energies that will excite it from $n=1$ to $n=2,3,4$ What this means is that photons with energy of 2 eV or 3.5eV or 4.5eV can be absorbed by the atom So the absorption spectrum of this element will show dark lines at these three photon energies. Once an atom has been raised to an excited state – in others words it has been raised up a level it will then drop down to a lower energy level and give off the energy difference as a photon $E_{photon} = E_{initial} - E_{final}$ The atom may return directly to the ground state with the emission of one photon or it may return via the different levels slowly and give off different photons. Foe example

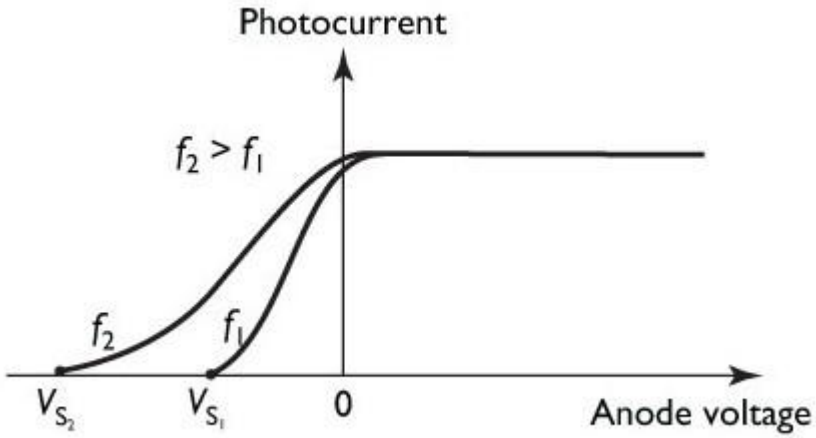
	 Looking at the diagram above the atom if the atom was excited to $n=3$ state it has a few options on how it will go down to the ground state level $n=1$ For example if may go directly to the ground state and give off a photon of 3.5eV Or it may drop to the $n=2$ and give off a 1.5eV photon and then go to the ground state and give off a 2eV photon.
Electron standing waves and atomic stability	In simple terms each quantized energy level of an atom represents a state where an electron circles the nucleus in a stable circular orbit. Electrons have a de Broglie wavelength λ, so for an orbit to be stable a whole number of electron wavelengths must fit into the circumference of the orbit. For example $n\lambda = 2\pi r$ and $n = 1,2,3$ In the diagram below , $n=4$, so that four electron wavelengths fit into the circumference  The diagram shows that four electron wavelengths fit the circumference The allowed orbits correspond to electron waves that constructively interfere to form a stable standing wave pattern. If the electron wave does not 'fit' it will destructively interfere and the orbit will not be stable.
In summary about Photons	Light is given off (emitted) and absorbed in discrete bundles or packets of electromagnetic energy called photons or quanta. A photon of frequency f (hz) has energy given by $E_{photon} = hf$ (measured in Joules) Planck's constant is $6.63\times10^{-34} J$ or $4.14\times10^{-15} eV$ - gives energy in eV Remember light is ROYGBIV and B is higher frequency than Red light so

	A photon of blue light carries more energy than a photon of red light. Photons travel at the speed of light therefore we have the following equation- $E_{photon} = \frac{hc}{\lambda}$ Increasing the intensity of light while keeping a constant frequency means increasing the number of photons but not changing the energy of the individual photons. Individual photons have a momentum of $p = \frac{h}{\lambda}$, but they do not have a mass or electric charge
Electron volt	The work done when an electron moves through a potential difference of 1 volt is given by the formula $W = qV$ So $W = 1.6\times10^{-19}\times1 = 1.6\times10^{-19}\,J$ Therefore $1eV = 1.6\times10^{-19}\,J$ The electron volt (eV) is convenient unit of energy for describing interactions involving atoms and electrons.
Photoelectric effect	If light shines on a metal cathode in an evacuated glass tube at a certain frequency of light electrons are ejected and make their way to the anode- this is the photoelectric effect.  The electrons also called photoelectrons are collected at the anode. They flow around the circuit back to the cathode. The ammeter measures the current. Key observations 1. For each cathode material (or different metals) there is a minimum or threshold frequency, f_0, below which no electrons are emitted. 2. There is no time delay between the arrival of the light and the emission of electrons. 3. For increasingly positive anode voltages the current increases until all the emitted electrons are collected. 4. As the negative retarding anode voltage increases more and more of the electrons are repelled. The current becomes zero at the stopping voltage 5. The stopping voltage V_s is a direct measure of the maximum kinetic energy of the electrons (in eV)- $E_{K-\max} = V_s$ 6. If the intensity of the incident light is increased- the stopping voltage does not change but the current increases in direct proportion to the intensity



7. For frequencies below the threshold frequency, f_0, there is no photoelectric effect.
8. For frequencies above, f_0, it is found that as the frequency of the light increases the required stopping voltage also increases

Notice the diagram



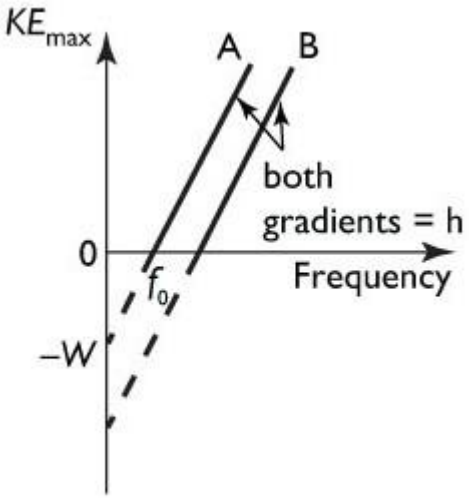
For example the two lines on the graph show how the light intensity is constant but the frequency is increased $f_2 > f_1$

This shows that the maximum kinetic energy of the electrons or photoelectrons (just another name) increases with the frequency of the light used.

Why the photoelectric effect showed the failure of the wave model to explain completely?

If light is a wave a beam of light should gradually deliver energy to the cathode surface until the electron acquires enough energy to escape. However detailed predictions of the wave model disagree with experimental observations

Predictions of wave model	Observations
There should be a time delay before any electron gains enough energy to escape	No measurable time delay even with low intensity light
The kinetic energy of the electrons should increase with light intensity	The maximum kinetic energy of the photoelectrons is independent of light intensity
The frequency (or colour) of the light should have no influence on photoelectric emission	There is a threshold frequency below which no emission occurs
The kinetic energy of the emitted electrons should be independent of the frequency of light	The maximum kinetic energy of photoelectrons is a linear function of the light frequency

Some explanations of key words	1. The smallest amount of energy required to free an electron is called the work function 2. At the threshold frequency a photon delivers just enough energy to free the least tightly bound electron 3. Light with frequency below threshold frequency cannot eject photoelectrons because the photon energy is less than the work function 4. For light $f > f_0$, the maximum kinetic energy of a photoelectron is $E_{K-\max} = E_{photon} - W = hf - hf_0$, so kinetic energy increases linearly with frequency. 5. Increasing the light intensity increases the number of photons and so the current increases with the intensity 6. The graph of Kinetic energy versus frequency shows the following properties.  Beware- the energy scale may be in units of J or eV. The graph above is consistent with the photon model Both graphs are straight lines with the gradient equal to h- Plancks constant The intercept on the horizontal axis is f_0 - the threshold frequency The intercept on the vertical axis is $-W$ (the work function) Material B has the higher threshold frequency and work function
A few more facts on photoelectric effect	The energy of a light beam = number of photons × photon energy Increasing the intensity of light at a constant frequency means increasing the number of photons but without changing the energy of individual photons