Light?

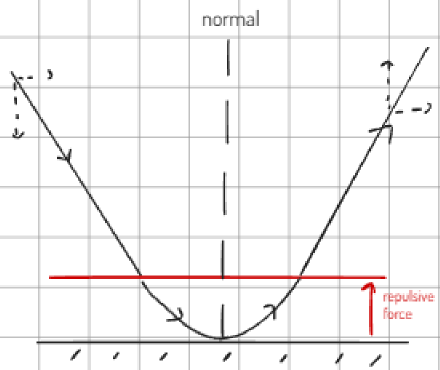
The end of the 17th century saw conflicting view on the nature of light.

Newton's Corpuscular Theory

Newton proposed that light behaved like a stream of particles.
These particles travel in straight lines unless refracting or reflecting.

Reflection

Reflection assumes that as corpuscles of light approaches a reflective surface they experience a REPULSIVE FORCE, perpendicular to the boundary. This force occurs over a very small region of space.



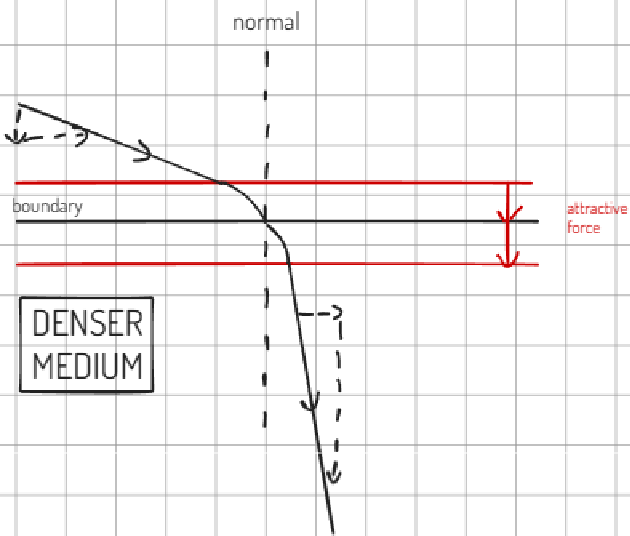
The vertical component will DECREASE to 0 and then INCREASE in the opposite direction.

The horizontal component will be CONSTANT.

The overall speed of light will be CONSTANT after reflection, so the angle of incidence will equal the angle of reflection.

Refraction

As light approaches a boundary between two transparent media the corpuscle experiences a ATTRACTIVE force. This force will act in a small region perpendicular to the boundary, and be directed towards the denser medium.



The horizontal component (parallel to the boundary) will be UNAFFECTED.

The vertical component (parallel to the normal) will increase in the direction of the denser medium.

This will change the path of the corpuscle TOWARDS THE NORMAL and the speed will be LARGER in the denser medium.

LIGHT IS A PARTICLE

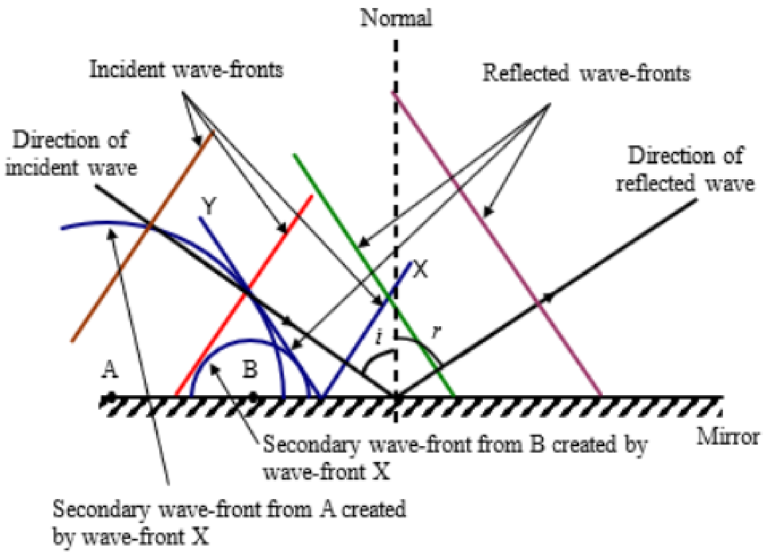
Colours of Light

Newton explained that different colour are just different kinds of corpuscles. When mixed together, they produce white light, but when they REFRACT, they experience slightly different attractive forces, so split into a spectrum.

Huygen's Wave Theory

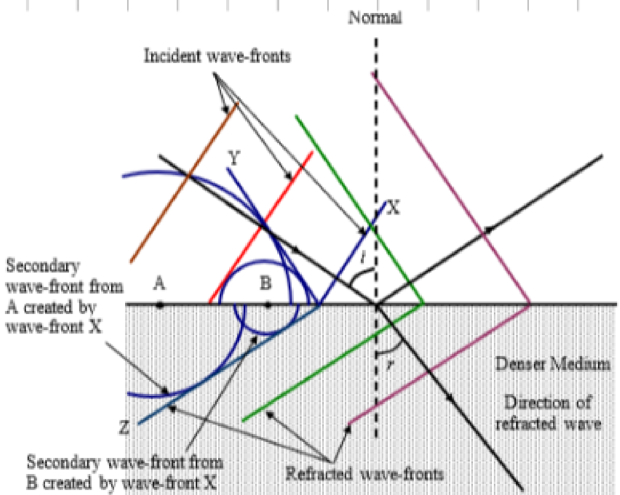
Huygen's proposed that each point on a wave of light acted as a secondary source, which produced waves, spreading out in circles from the original point. The resulting final wave was constructed by superposition.

Reflection according to Huygens



The incoming wave X hits the mirrored surface, moving from left to right (along the boundary towards the normal). This causes secondary wavelets to be produced along the surface of the mirror. Two examples are shown, A and B. The secondary waves spread out from A and B, and interfere producing a reflected wavefront, the wave from A travels further than B as it was produced earlier.
The secondary wavefront then produces further wavefronts (based on Huygens theory) as the wave propagates away from the mirror.

Refraction



The wave (as in reflection) moves across the boundary producing secondary wavelets.
Parts of these secondary waves produces now travel MORE SLOWLY in the denser medium.
The refracted wave is found by joining these slowly moving wavelets, giving a wavefront with a ray which appears to bend TOWARDS THE NORMAL.

Newton's theory clearly indicates that waves should be FASTER in a denser medium, whilst Huygen's proposes that waves will SLOW DOWN.

LIGHT IS A WAVE?

The Ether

There was no example of a wave which could propagate through vacuum. So Huygens invented a medium called the luminiferous ETHER, through which light could travel to the Sun and Stars.

The Dominance of Newton

Reputation

Newton was well regarded, and had several high profile discoveries to his name. He was probably right...

Shadows

When a large opaque object is placed in the path of light, it creates a shadow.
In wave theory, light should bend around the object, creating no shadow.
Particles can only travel in straight lines, producing a shadow as they cannot traverse the object.

Light in a vacuum

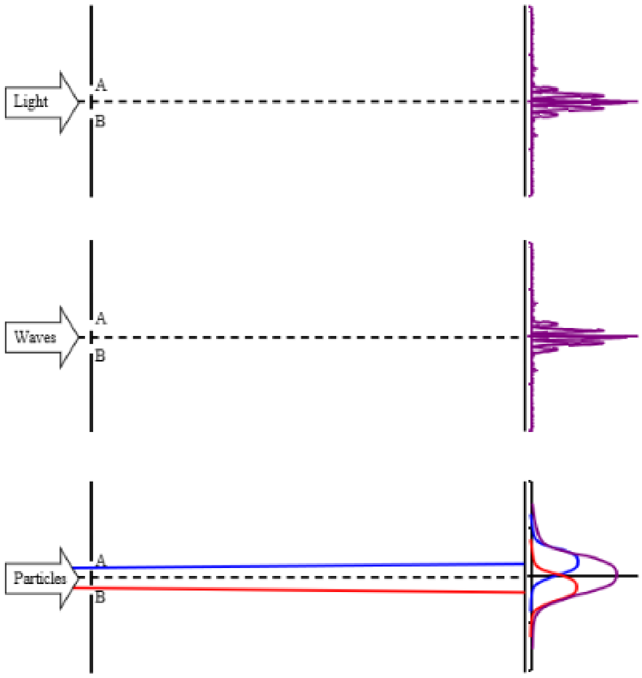
There is no evidence for the ether. It was believed that waves required a medium, whilst particles did not.

The speed of light

There was no clear measurement of the speed of light, which made it impossible to determine if light sped up or slowed down when refracted.

1807

Evidence for Huygen's



Young's double slit experiments provided early evidence of the wave nature of light.

This led to observations of diffraction, superposition and interference, all supporting Huygen's theory.

However, the conclusion were poorly communicated, so it took time for the scientific community to support the ideas still.

This was later developed by Fresnel, who produced a mathematical treatment of diffraction, and show that diffraction was only apparent when the wavelength of light was comparable to the magnitude of the object. (large objects and short wavelengths can cast shows)

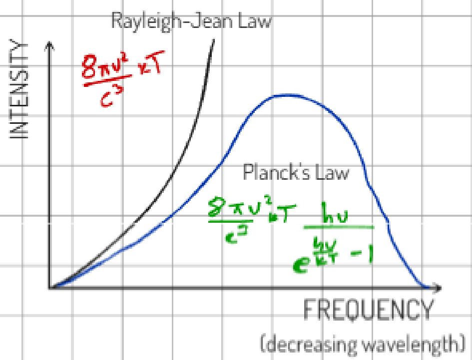
In 1850 Foucault measured the speed of light in air and water. He found light was SLOWER in water than in air.
This cemented Huygen's theory over Newton's.

LIGHT IS A WAVE !

The Ultraviolet Catastrophe

A black body is a body that emits all the possible wavelengths of radiation for the temperature that it's at.

Classical theory predicted that most of the energy would be emitted in the UV range, and would be infinite at the very smallest wavelengths.



Observed data show there is a peak at a longer wavelength than expected, and that it appears at a shorter wavelength as temperature increases.

This was explained by Max Planck

Planck explain this by modelling light AS A PARTICLE.

LIGHT IS A PARTICLE?

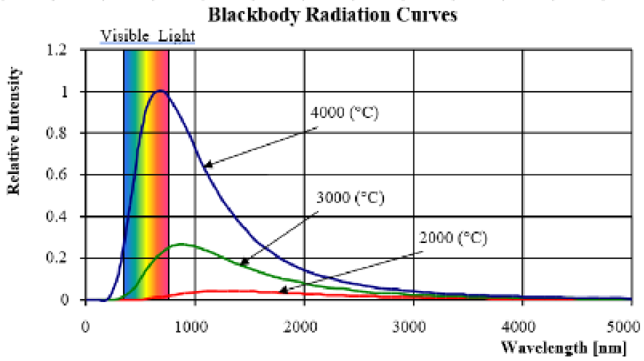
Light experiences WAVE-PARTICLE DUALITY

Light as a particle

TURNING POINTS

QUANTUM

A blackbody is a perfect absorber and emitter of EM radiation.



In classical wave theory the relative intensity tends to infinity around the UV region of the spectrum.

By making a few assumptions, Max Planck was able to model these distributions:
- The radiation emitted was not continuous.
- The radiation emitted consisted of discrete packets of energy, known as QUANTA.
- A black body can only emit integer numbers of each quanta.

Quanta of EM radiation later became known as PHOTONS.

Planck suggested that the energy of these quanta was linked to the frequency of the light emitted.

$$E = hf$$

E - energy of the photon [J]
f - frequency of light [Hz]
h - Planck's constant $= 6.63 \times 10^{-34}\ Js$

$$1\ eV = 1.6 \times 10^{-19}\ J$$

REMINDER

Planck postulated that photons:
- Carry DISCRETE amounts of energy
- When they interact with matter they are absorbed or emitted AS WHOLE QUANTA.

Photoelectricity

In 1902, Phillip Lenard conducted an experiment with visible and ultraviolet light. He found that when incident on a sheet of metal, some of the incident waves could cause electrons to be emitted. These are known as PHOTOELECTRONS, released by the PHOTOELECTRIC EFFECT.

The observation made were:
1. Emission of photoelectrons ONLY occur if the frequency was above a minimum value. This became known as the THRESHOLD FREQUENCY. This was dependent on the type of metal used.
2. The emission of photoelectrons happens almost immediately after the metal is illuminated.
3. Above the threshold frequency, the number of photoelectrons emitted per second is proportional to the INTENSITY of the incident light.

INTENSITY
The energy incident on a surface per unit time per unit area
$[W\ m^{-2}]$

INTENSITY = Number of photons incident per unit area per second x Energy of a single photon

4. The photoelectrons emitted have a range of kinetic energies, from zero up to a maximum value.
5. Above the threshold frequency, the maximum kinetic energy depends on the FREQUENCY of the incident light. (but is unaffected by the INTENSITY).

Failure of Wave Theory

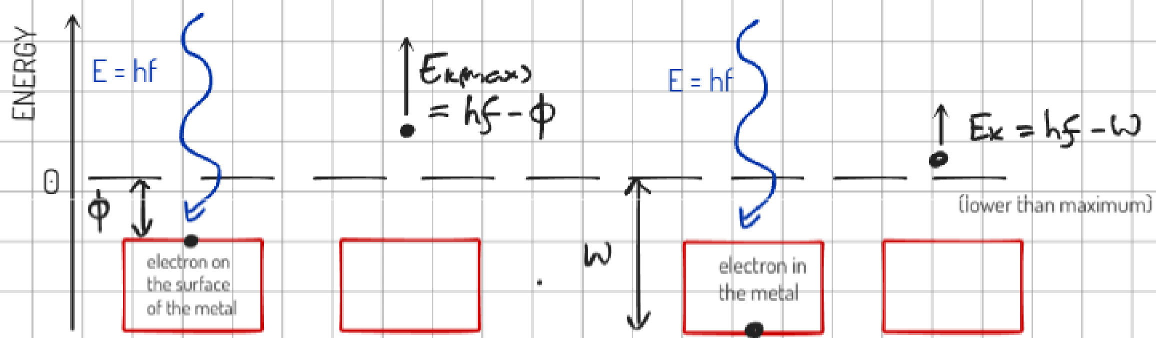
The wave theory of light of light cannot explain the experimental observations of the photo-electric effect. According to the wave theory of light, electrons in the metal would absorb energy gradually and continuously, when the electrons acquire sufficient energy they could overcome the electrostatic attraction of the ions in the metal, allowing them to be emitted:

1. There would be a time delay between the metal being illuminated and photoelectrons being emitted, there should not be any instantaneous emissions of photoelectrons.
2. According to the wave theory of light the intensity of light depends on the amplitude of the light waves.
3. There would be no threshold frequency as even light of low frequency would eventually be able to emit photoelectrons, in a reasonable time, provided the amplitude of the light waves was high enough.
4. Increasing the intensity of the light could increase the energy delivered to photoelectrons, increasing the maximum KE of photoelectrons.

Along came Einstein

Einstein assumed that the incident light was composed of a BEAM OF PHOTONS.
When interacting with the metal, each photon could be reflected, or ABSORBED BY A SINGLE ELECTRON.

This means that as soons as one electron interacts with one photon (provided that photon had enough energy) the electron would be immediately emitted. The kinetic energy of the emitted electron would depend on the frequency of the photon it has absorbed. And the number of electrons emitted would depend only on the number of incident photons.



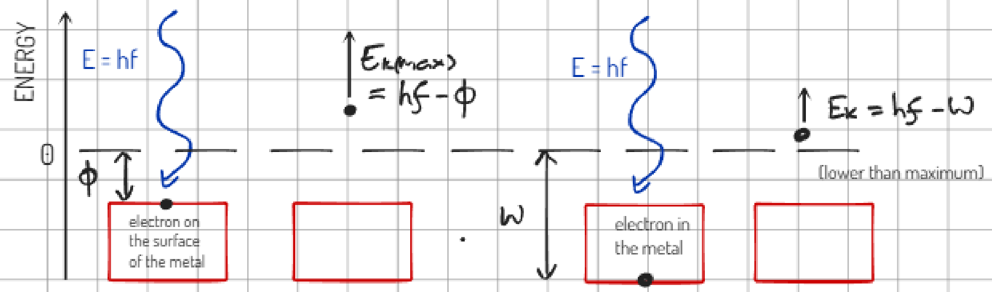
ϕ is the WORK FUNCTION. This is the MINIMUM energy required to remove an electron from the SURFACE OF THE METAL.
Electrons emitted in this way have MAXIMUM KINETIC ENERGY.

$$hf = \phi + \frac{1}{2} m v_{max}^2$$

TURNING POINTS

QUANTUM

The Photoelectric Effect



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$$hf = \phi + \frac{1}{2}mv_{max}^2$$

When illuminated by MONOCHROMATIC LIGHT (single frequency) all photons transfer the same amount of energy when a single photon is absorbed by a single electron.

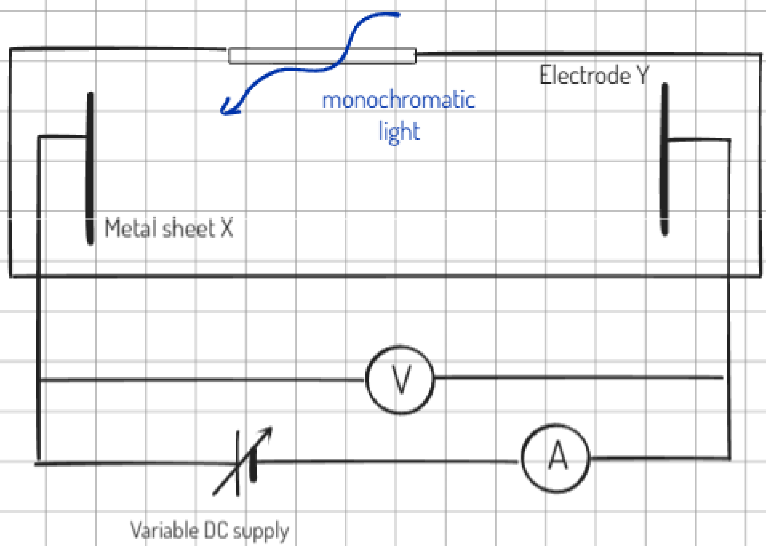
Electrons can escape the metal if the energy of the photon is sufficiently high, with the excess being stored as kinetic energy in the liberated electron.

Different electrons within the metal start with different energies. The closer to the surface of the metal the electrons are located, the MORE ENERGY they have. This means they require a LOWER ENERGY to be LIBERATED.

Electrons ON THE SURFACE of the metal require the MINIMUM AMOUNT OF ENERGY to be emitted (this is called the WORK FUNCTION). These electrons will have MAXIMUM KINETIC ENERGY.

Electrons liberated from other parts of the metal may require more energy, leading to a range of kinetic energies across emitted electrons.

Experimental Verification of Einstein's Explanation



The sheet X is illuminated with monochromatic light. Photoelectrons are emitted with a range of kinetic energies. Some of these photoelectrons travel to electrode Y, causing a current to flow between X and Y.

A potential difference is applied between Y and X. This produces and electric field between the plates and the pd was increased until current dropped to zero. This means that even the electrons with maximum kinetic energy were unable to reach Y.

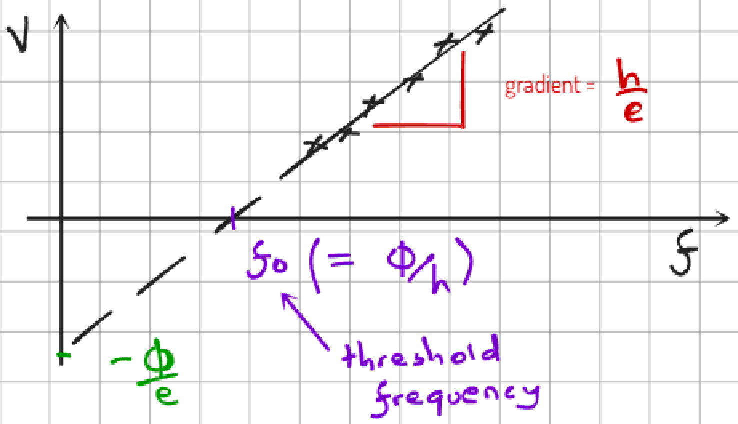
This is called the STOPPING VOLTAGE.

We can apply the law of conservation of energy here:

$$\frac{1}{2}mv_{max}^2 = eV_s$$

LOSS IN KE — GAIN IN PE $(E = QV)$

We can also plot the data in terms of the maximum kinetic energy of the electrons.

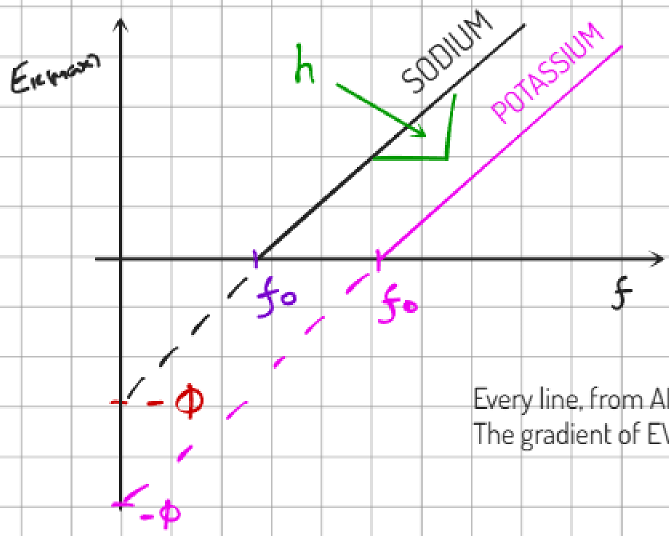


$$hf = \Phi + \frac{1}{2}mv^2_{max}$$

$$\boxed{hf = \Phi + eV_s}$$

$$V_s = \boxed{\frac{h}{e}} f - \boxed{\frac{\Phi}{e}}$$

$$y = m x + c$$



$$hf = \Phi + E_{k(max)}$$

$$E_{k(max)} = \boxed{h} f \boxed{- \Phi}$$

$$y = m x + c$$

Every line, from ANY METAL will be PARALLEL.
The gradient of EVERY LINE will be h.

Q1.

The photoelectric effect can be demonstrated by illuminating a negatively charged plate, made from certain metals, with ultraviolet (UV) light and showing that the plate loses its charge.

(a) Explain why, when ultraviolet light is shone on a **positively** charged plate, no charge is lost by the plate.

The process involves the ejection of electrons which are negatively charged. ✓

Any electrons ejected will only make the positive charge greater. ✓

(2)

(b) Threshold frequency and work function are important ideas in the study of the photoelectric effect.

Tables 1 and **2** summarise the work functions of three metals and photon energies of three UV light sources.

Table 1

Metal	Work function / eV
Zinc	4.3
Iron	4.5
Copper	4.7

Table 2

Light source	Photon energy / eV
1	4.0
2	4.4
3	5.0

Discuss the combinations of metal and UV light source that could best be used to demonstrate the idea of threshold frequency and the idea of work function.

To demonstrate threshold frequency:

- The metal should be kept the same and the light source varied.
- Using any metal, and light sources 1 and 3, no charge will be lost with light source 1 but charge will be lost with light source 3
- Because light source three has a greater photon energy and therefore frequency (from E=hf) and is above the threshold frequency (or the photon energy is greater than the work function of the metal), whilst light source 1 has a photon energy less than the work function of the metal, so is below the threshold frequency.

To demonstrate work function

- The light source should be kept the same, and the metal varied
- Use light source 2 as the other two will either cause all three metals to lose their charge or none of the metals to lose their charge.
- Use each metal in turn, so that zinc loses its charge, due to its low work function but copper and iron do not lose their charge.

(6)

(c) Calculate the maximum kinetic energy, in J, of the electrons emitted from a zinc plate when illuminated with ultraviolet light.

work function of zinc = 4.3 eV

frequency of ultraviolet light = 1.2×10^{15} Hz

$$E_{k(max)} = hf - \Phi \checkmark$$

$$= (6.63 \times 10^{-34} \times 1.2 \times 10^{15}) - (4.3 \times 1.6 \times 10^{-19}) \checkmark$$

$$= 1.0 \times 10^{-19} \text{ J} \quad \text{(allow 1.1)}$$

maximum kinetic energy ____________________ J

(3)

(d) Explain why your answer is a maximum.

The work function is the minimum amount of energy needed to remove the electron from the zinc surface ✓

OR Max KE corresponding to emission of surface electrons whilst electrons from deeper in the metal will be emitted with smaller KE ✓

(1)

(Total 12 marks)

Atomic Line Spectra

Bohr Model of the Atom

The simplest atom to understand is HYDROGEN.

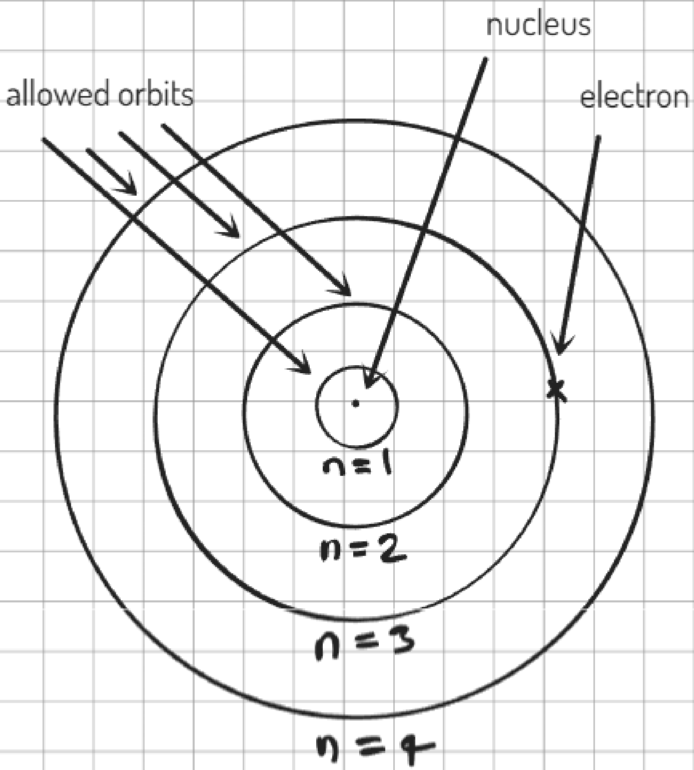
Hydrogen consists of a single electron orbiting a nucleus.

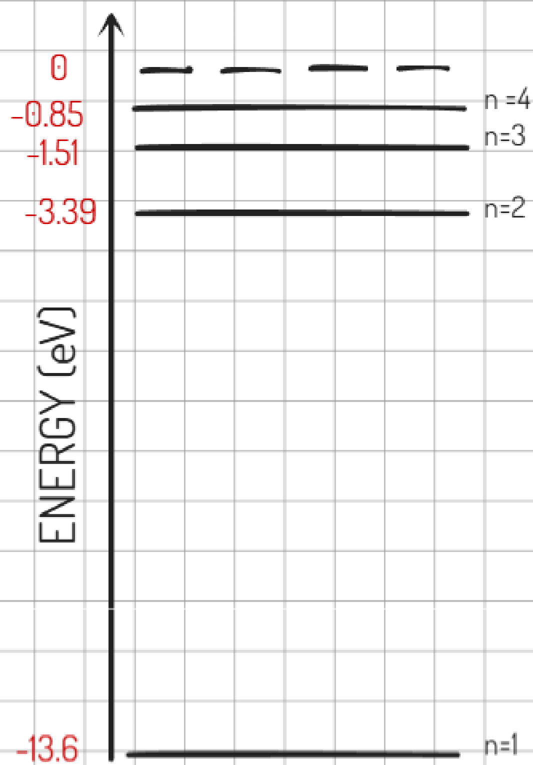
The electron is only able to orbit the nucleus at certain DISCRETE distances. These are known as the ALLOWED ORBITS.

Each orbit represents a different ENERGY STATE of the electrons, so are represented as ENERGY LEVELS.

An electron (when it absorbs a discrete amount of energy) may be EXCITED to a higher energy level.

Or it may DE-EXCITE to a lower energy level, emitting a discrete amount of energy as a PHOTON of EM RADIATION.





The orbit with the LOWEST POSSIBLE ENERGY (n =1) is known as the GROUND STATE. All higher DISCRETE energy levels are known as EXCITED STATES.

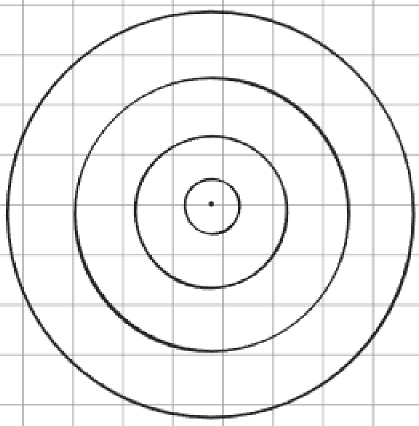
A FREE ELECTRON which has been liberated will have at least 0eV of energy.

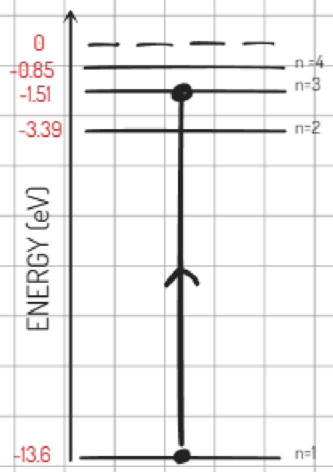
29/02/24

Atomic Line Spectra

QUANTUM

EXCITATION





When an electron in a lower DISCRETE energy level absorbs energy, it CAN move up to a higher energy level.

This is known as EXCITATION.

The movement from one level to another is called a TRANSITION.

Electrons can absorb this energy from:
- A DISCRETE photon of EM radiation
- KINETIC ENERGY transferred by a FREE ELECTRON (or other particle)

The energy absorbed must be EXACTLY EQUAL TO THE DISCRETE DIFFERENCE BETWEEN THE ENERGY LEVEL.

$$\Delta E = E_3 - E_1 = (-1.51) - (-13.6)$$
$$= 12.09\,eV$$

So, a photon incident on the sample would need to have an energy of 12.09 eV to cause this excitation.

$$f = \frac{E}{h} = \frac{(12.09 \times 1.6\times10^{-19})}{6.63\times10^{-34}} = 2.9\times10^{15}\,Hz$$

A free electron with an initial kinetic energy of 20 eV interacts with the orbital electron, causing it to transition from n=1 to n=3. Use the law of conservation of energy to calculate the final kinetic energy of the free electron.

$$E_{ki} = E_{kf} + \Delta E \qquad E_{kf} = E_{ki} - \Delta E$$
$$= 20 - 12.09$$
$$= 7.91\,eV$$

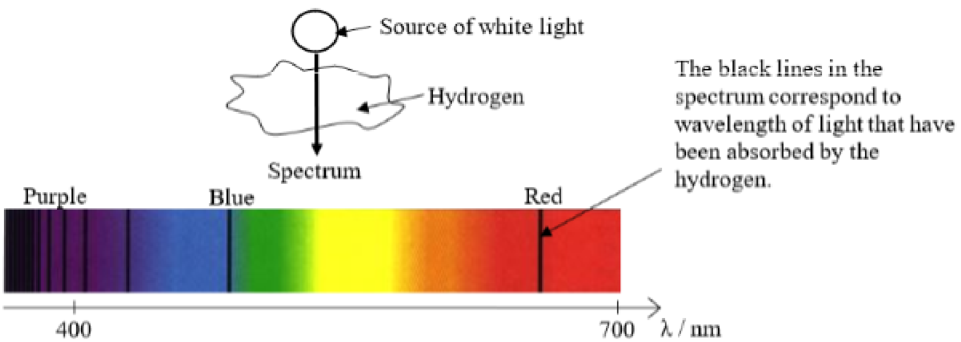
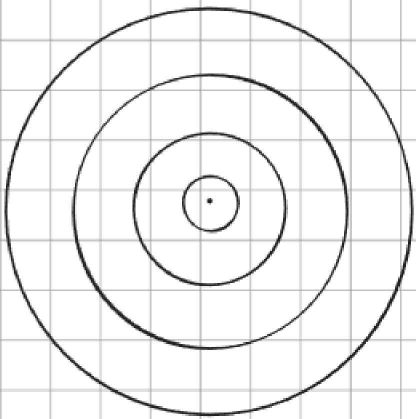


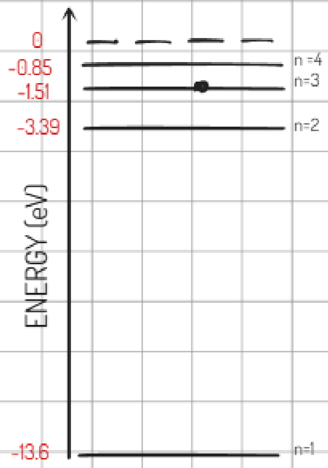
Figure 4: The absorption spectrum of hydrogen

If we illuminate a gas of a particular element with white light (which is a continuous spectrum of all visible wavelengths) then we will see BLACK LINES present at DISCRETE FREQUENCIES which have been absorbed by the gas. This is known as an ABSORPTION SPECTRUM.

These spectra can be used to study the compositions of stars and stellar atmospheres.

DE-EXCITATION



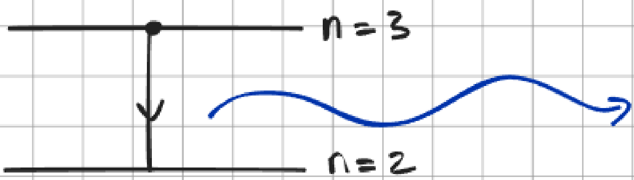


When an electron in an atom has been excited it usually DE-EXCITES.

The electron LOSES ENERGY as it transitions to a lower energy level by:

- emitting ONE OR MORE photons of EM radiation.

This process happens spontaneously after a short time.



$$\Delta E = E_3 - E_2 = (-1.51) - (-3.39) = 1.88\,eV$$

The energy of the emitted photon is DISCRETE, and is equal to the difference in energy between the two DISCRETE energy levels. This means the frequency of the emitted photon is also DISCRETE.

$$f = \frac{(1.88 \times 1.6 \times 10^{-19})}{6.63 \times 10^{-34}} = 4.5 \times 10^{14}\,Hz$$

$$\lambda = \frac{3 \times 10^8}{4.5 \times 10^{14}} = 6.61 \times 10^{-7}\,m = 661\,nm$$

SO RED

Atomic Line Spectra

QUANTUM

IONISATION

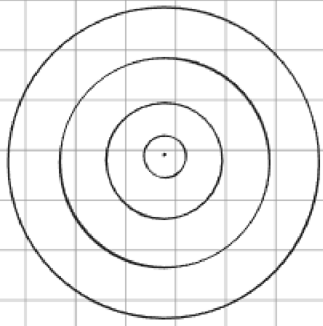
In an IONISATION transition, an electron within the orbitals immediately becomes a FREE ELECTRON.

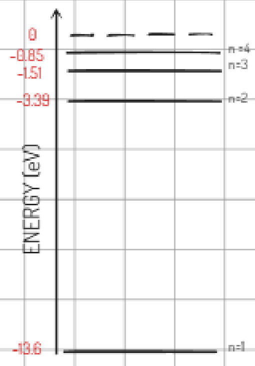
This creates a POSITIVE ION and FREE ELECTRON.

The MINIMUM energy of a free electron is defined as 0 eV.

For ionisation, ANY PHOTON with an energy higher than the IONISATION ENERGY can cause this transition.

Excess energy is transferred to the KINETIC ENERGY store of the free electron.





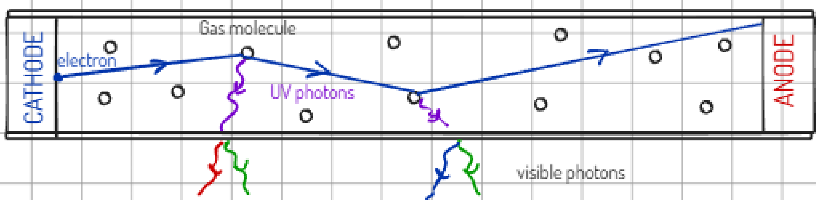
The IONISATION ENERGY is the minimum energy to remove an electron from the GROUND STATE (n=1).

$$\Delta E = 0 - (-13.6)$$
$$= +13.6 \text{ eV}$$

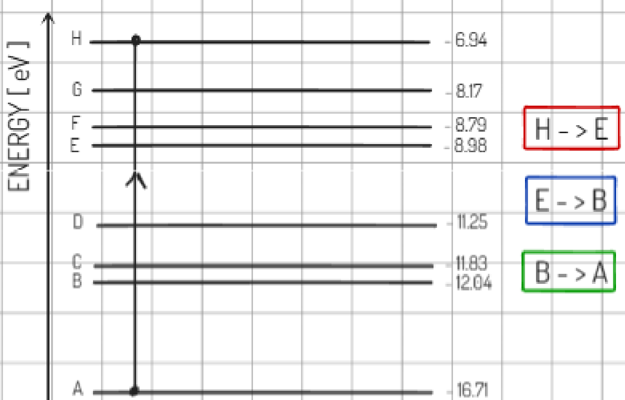
FLUORESCENCE

Fluorescent lights depend on the excitation and de-excitation of electrons, to produce a line spectrum of light.

An electric current flows through a tube. Freely moving electrons are accelerated between an cathode and an anode. These electron collide with atoms of a low-pressure inert gas which fill the tube, transferring some of their kinetic energy to the orbital electrons in the gas, exciting them. These electrons then de-excite and emit photons of UV light.



These UV photons are absorbed by the powder coating the outside of the tube, exciting electrons within these atoms. These electron de-excite emitting several different, but specific wavelengths of light, leading to a visible line spectrum.



$$\Delta E = -6.94 - (-8.98)$$
$$= 2.04 \text{ eV}$$
$$= 3.3 \times 10^{-19} \text{ J}$$
$$f = 4.98 \times 10^{14} \text{ Hz}$$
$$\lambda = 601 \text{ nm}$$

ORANGE

$$\Delta E = -8.98 - (-12.04)$$
$$= 3.06 \text{ eV}$$
$$= 4.9 \times 10^{-19} \text{ J}$$
$$f = 7.38 \times 10^{14} \text{ Hz}$$
$$\lambda = 406 \text{ nm}$$

VIOLET

$$\Delta E = -12.04 - (-16.71)$$
$$= 4.67 \text{ eV}$$
$$= 7.5 \times 10^{-19} \text{ J}$$
$$f = 1.13 \times 10^{15} \text{ Hz}$$
$$\lambda = 266 \text{ nm}$$

NON-VISIBLE

Wave-Particle Duality

QUANTUM

Light

In order to explain the photoelectric effect, Einstein suggested that light was not just a wave (as described by classical electromagnetic theory) but also a particle.

Light can undergo reflection, refraction, diffraction and interference like any other wave and that it has wavelength and frequency. But light can also only be emitted and absorbed in discrete quanta, like a particle.

These quanta are called photons, and described by:

$$\boxed{E = hf} \qquad h = 6.63 \times 10^{-34}\, Js$$

So light is said to be simultaneously a wave and a particle, it experiences wave-particle duality.

De Broglie's Hypothesis

In De Broglie suggest that if light can be a particle, so surely, particles can be waves...

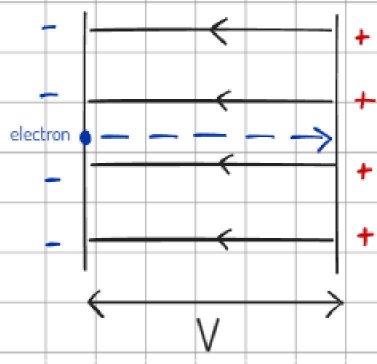
He suggested that particles could have a wavelength, and determined that these electron waves could be described with:

$$\boxed{\lambda = \frac{h}{p}} \qquad h = 6.63 \times 10^{-34}\, Js$$

$$p = momentum\ of\ particle$$

The wavelength of an electron

An electron is accelerated between two oppositely charged electrodes with a pd between them.



Lets begin from conservation of energy:

$$Gain\ in\ KE = Loss\ in\ PE$$

OR

$$\frac{1}{2}mv^2 = eV$$

$$mv^2 = 2eV$$

$$m^2v^2 = 2meV \qquad \boxed{mv = (2meV)^{1/2}}$$

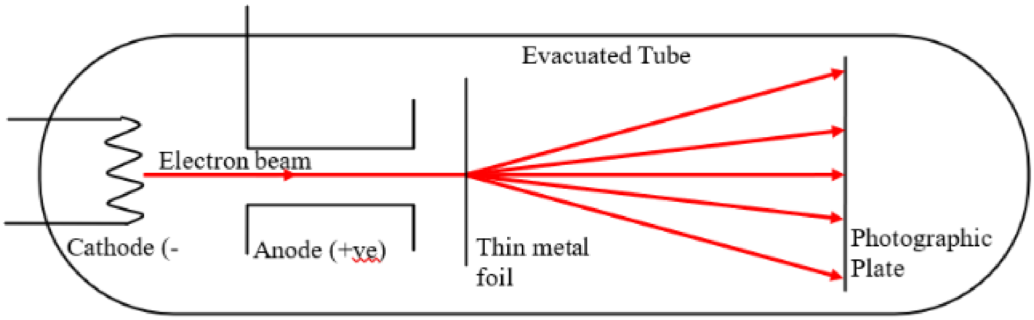
$$\lambda = \frac{h}{p} \qquad \boxed{\lambda = \frac{h}{(2meV)^{1/2}}}$$

$$\lambda = \frac{6.6 \times 10^{-34}}{(2 \times 9.11 \times 10^{-31} \times 1.6 \times 10^{-19} \times 100)^{1/2}} \quad \text{for } 100V$$

$$= 1.2 \times 10^{-10}\, m$$ approximate radius of an atom

Electron Diffraction

In 1928 experimental evidence supporting De Broglie's idea of electron waves was published.



Electrons were accelerated through a perforated anode before striking a thin metal foil and diffracting onto a photographic plate.

They produced a series of rings of different intensities arising from interference. The wavelength of the electrons was consistent with De Broglie's predictions.

The electron, like light is considered to have a wave-particle duality.

Other particles

All particles, even atoms and molecules should be able to exhibit wave-particle duality. This even applies to macroscopic collections of atoms.

Calculate the De Broglie wavelength of Andrew (82 kg) at a top speed of 8.5m/s

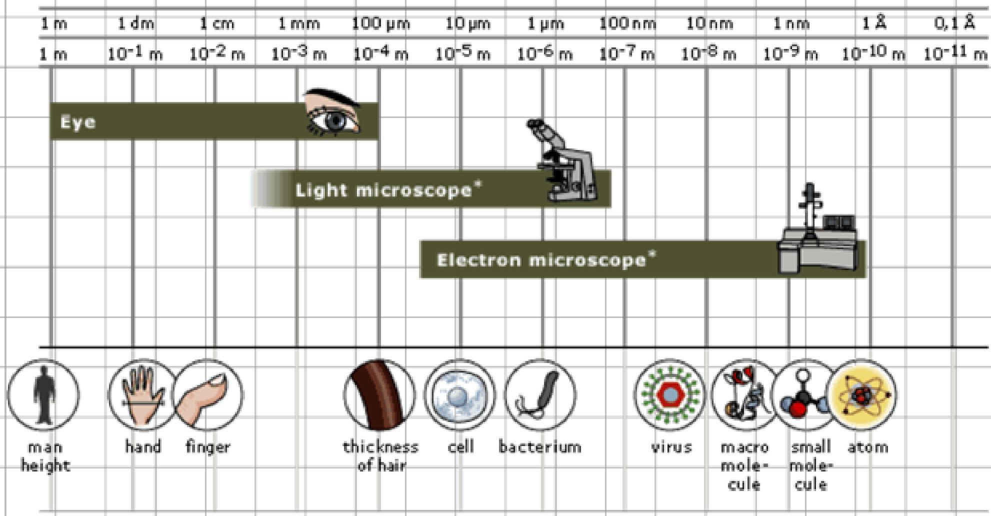
$$\lambda = \frac{h}{mv} = \frac{6.63\times10^{-34}}{82\times 8.5} = 9.5\times10^{-37}\ \text{m}$$

It is unlikely that a human being could fit through a gap comparable to their wavelength

In quantum mechanics, theory treats all particle and waves as PROBABILITY WAVES. They determine the probability of a particle being found in a given place.

Electron Microscopy

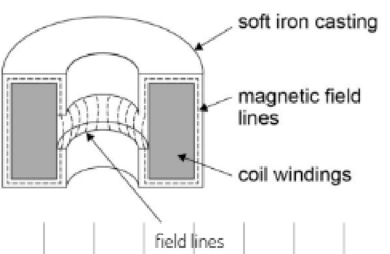
TURNING POINTS

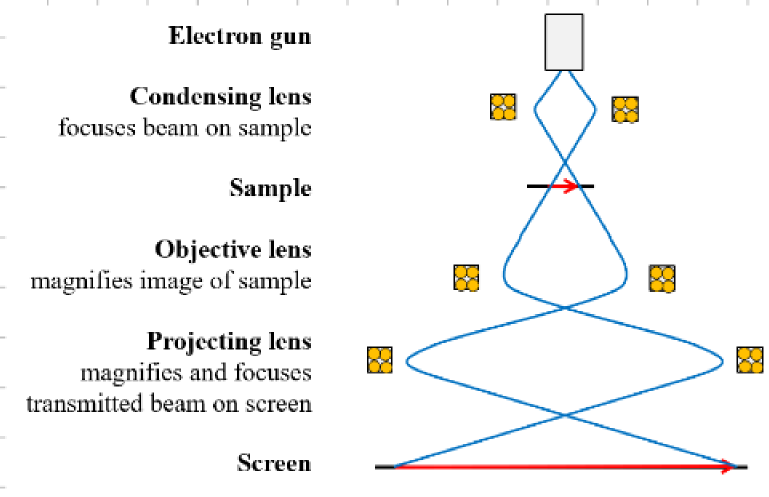


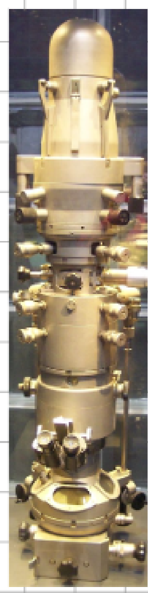
TEM

Transmission Electron Microscopy was developed in 1931 as a way of increasing the resolving power of images beyond that of visible microscopes.

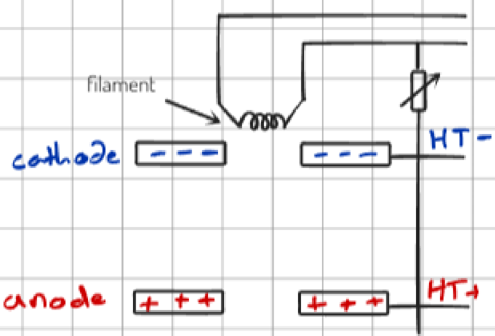
This involves producing and directing an electron beam onto a target, using a series of 'lenses' to focus and magnify the image produced.







The 'Electron Gun'



Electrons are emitted from the heated filament.
The current in the beam is around 1 microamp
The electrons are accelerated across a high pd between the anode and cathode.

Note: above 100kV some relativistic adjustments will be needed for the mass of the electron.

The Magnetic Lenses

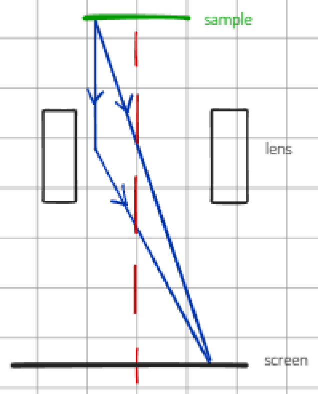
E_k gain = E_p loss

$$\frac{1}{2}mv^2 = eV$$

$$\frac{1}{2}\frac{p^2}{m} = eV \quad \text{so} \quad p^2 = 2meV$$

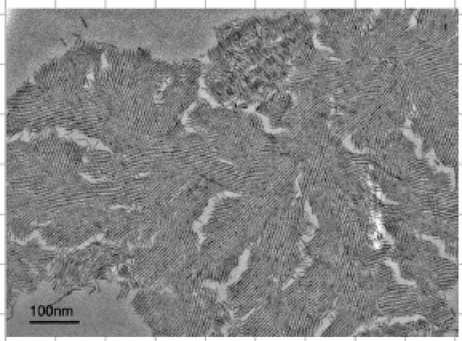
$$\lambda = \frac{h}{(2meV)^{1/2}}$$

Electrons passing near the inner edge of the lens is deflected towards the axis of the microscope. Electrons passing through the centre are undeflected.



The RESOLUTION of the image can be changed by:
- Increasing the accelerating potential difference.
- This increases the speed of the electrons.
- This increases the momentum of the electrons.
- This DECREASES the wavelength of the electrons.
- Improving the resolution of the image.

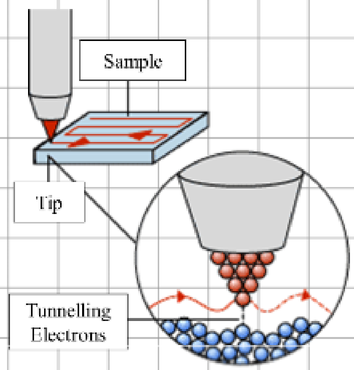
Limitations



- The sample needs to be very thinly sliced.
- The sample needs to be studied in a vacuum.
- The sample can be damaged by the passage of the electrons.
- There will be a range of speeds in the electron beam which limits resolution as the radius of curvature of an electron in a magnetic field depends on its speed.

STM

A Scanning Tunnelling Microscope studies the structure of a surface using a tip which scans the surface of a material.

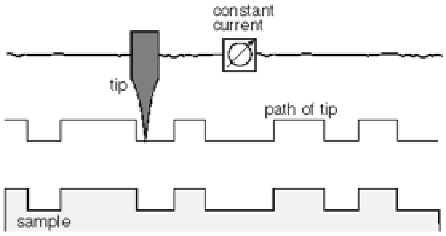


Electrons behaving like waves are able to cross the gap between the tip and the sample, despite not having sufficient energy to do so.

This is called QUANTUM TUNNELLING.

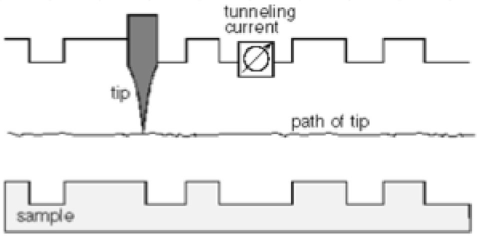
The size of the current depends on the distance between the tip and the sample. The bigger the distance, the smaller the current.

There are two different modes.



<u>**Constant Current Mode**</u>

- The tip is moved up and down as scans across the sample.
- This keep the current between the tip and the sample constant.
- The tip stays a constant height above the sample, to within $\pm 10^{-12}$ m .
- The position of the tip is recorded and the used to build up an image of the sample.



<u>**Constant Height Mode**</u>

- Tip travels across the sample in a horizontal plane.
- The current changes depending on the distance to the sample.
- The current is measured as the tip scans across the sample
- The current is used to construct and image of the surface
- This mode is used when the distance between gaps is small and the microscope needs to respond to rapid changes in profile