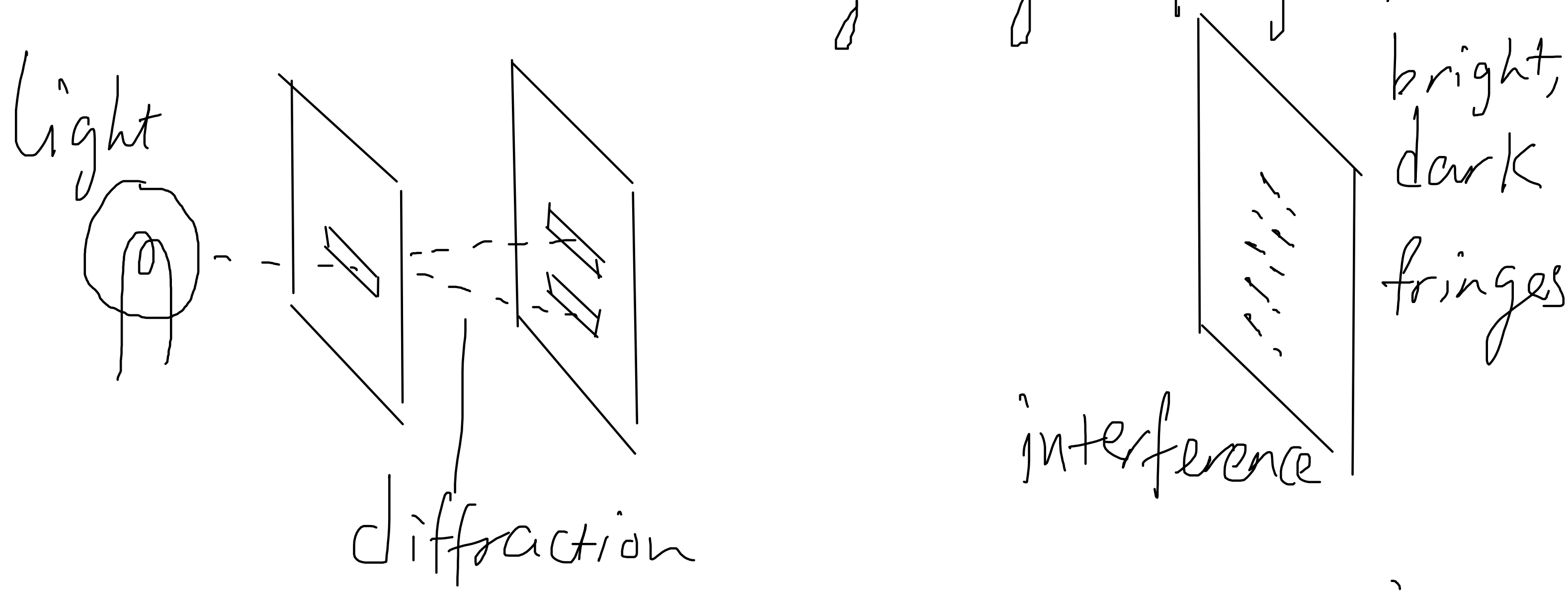
Light is made up of particles??

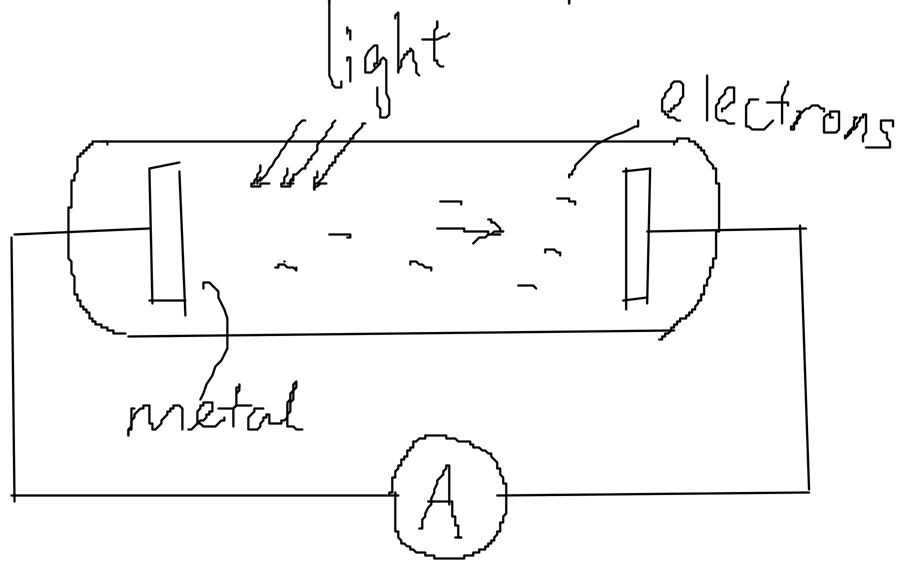
Dr K M Hock

We are quite sure that light is a wave.

It cannot be particles – stones can't interfere destructively to give fringes!



But only light above certain frequency can remove electrons from metal.



Einstein showed this implies light is also particles!?

Photon Energy

Dr K M Hock

Einstein showed that the energy of each particle of light is $E = hf$

where f = frequency

$h = 6.63 \times 10^{-34}$ J.s (Planck's constant)

(wiki)

Color	Frequency	Wavelength
violet	668–789 THz	380–450 nm
blue	606–668 THz	450–495 nm
green	526–606 THz	495–570 nm
yellow	508–526 THz	570–590 nm
orange	484–508 THz	590–620 nm
red	400–484 THz	620–750 nm

e.g. A red light has a frequency of 450 THz.

Then a particle of this light has energy

$E = hf = 6.63 \times 10^{-34} \times 450 \times 10^{12} = 2.984 \times 10^{-19}$ J

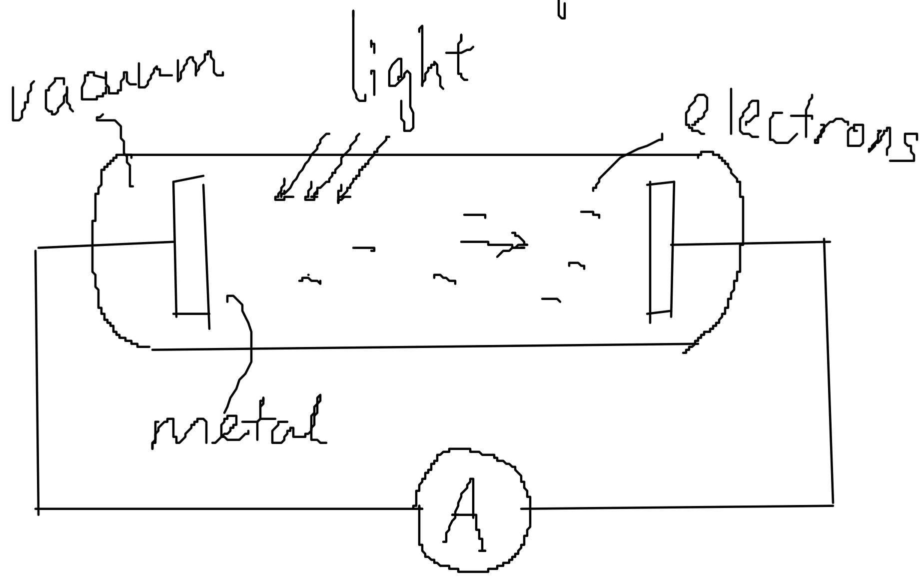
Particle of light – Photon.

show an understanding that the photoelectric effect provides evidence for a particulate nature of electromagnetic radiation while phenomena such as interference and diffraction provide evidence for a wave nature

Photoelectric Effect

Dr K M Hock

But how did Einstein deduce that light consisted of particles?



In this set up, a current flows when light shines on the metal.

But if the light frequency is below some value (threshold), no current flows – no matter how bright.

If light is a wave – no way to explain

Einstein: – maybe light consists of particles
– and energy of each particle increases with frequency.

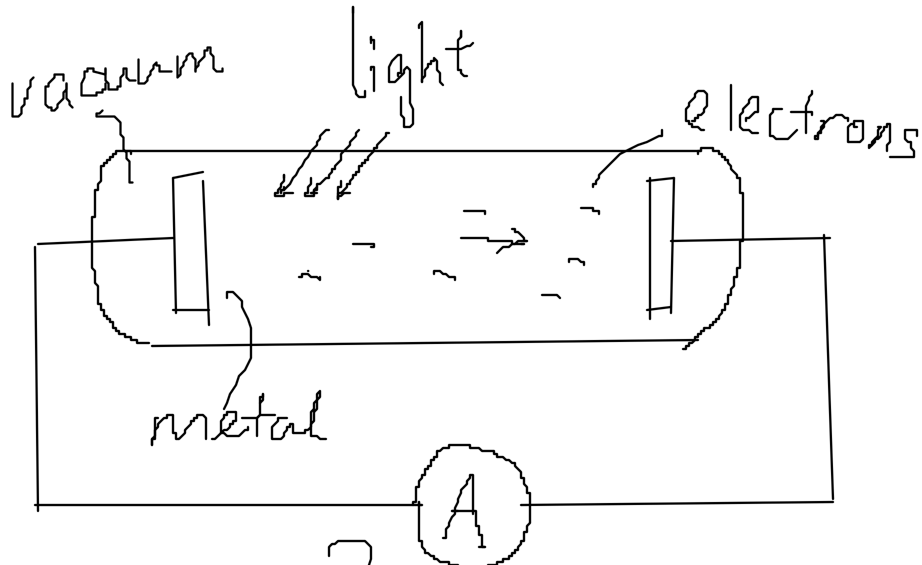
Low frequency – light particle not enough energy to remove electron from metal.

Threshold Frequency

Dr K M Hock

ϕ Work function – minimum energy to remove an electron from a metal.

e.g. Work function of Sodium is 2.36 eV.



What frequency of light is needed to produce a photoelectric current?

$$E = hf \quad f = \frac{E}{h} = \frac{2.36 \times 1.6 \times 10^{-19}}{6.63 \times 10^{-34}}$$

$$= 569.5 \text{ THz}$$

(what colour?)

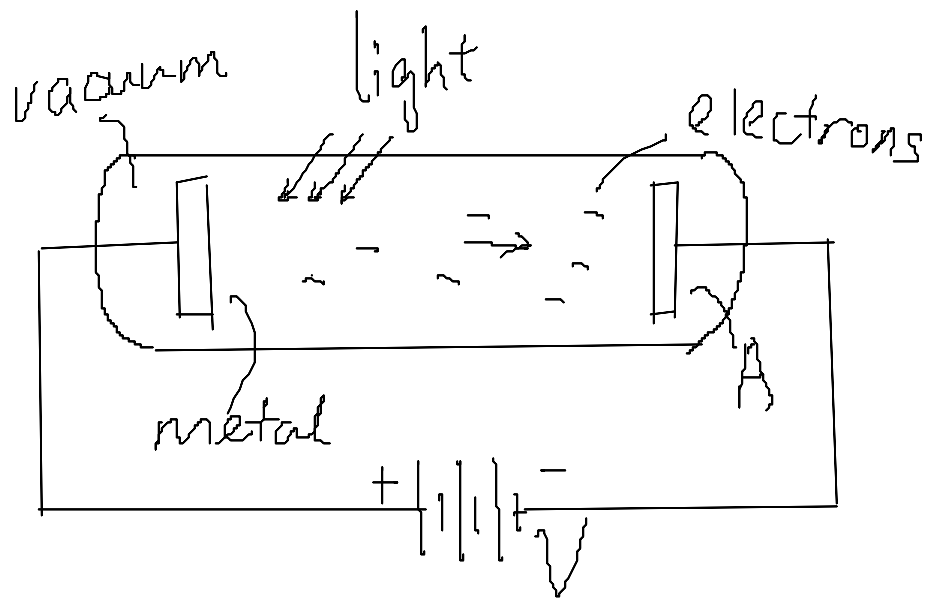
e.g.

	ϕ eV	(Wiki)
silver	4.26	
gold	5.1	
aluminium	4.06	
copper	4.53	
tin	4.42	
iron	4.67	

Stopping Potential

Dr K M Hock

If we apply a -ve voltage to anode A, the photoelectrons slow down.



If V is big enough, current stops.
↓
stopping potential V_s.

KE of electron just fail to do work needed to overcome V_s.

$$\underset{KE}{\frac{1}{2} m_e v_{max}^2} = \underset{work}{eV_s}$$

Photoelectron has a range of velocities.

v_{max} = largest.

i.e. V_s is when even e^- which highest KE cannot overcome V.

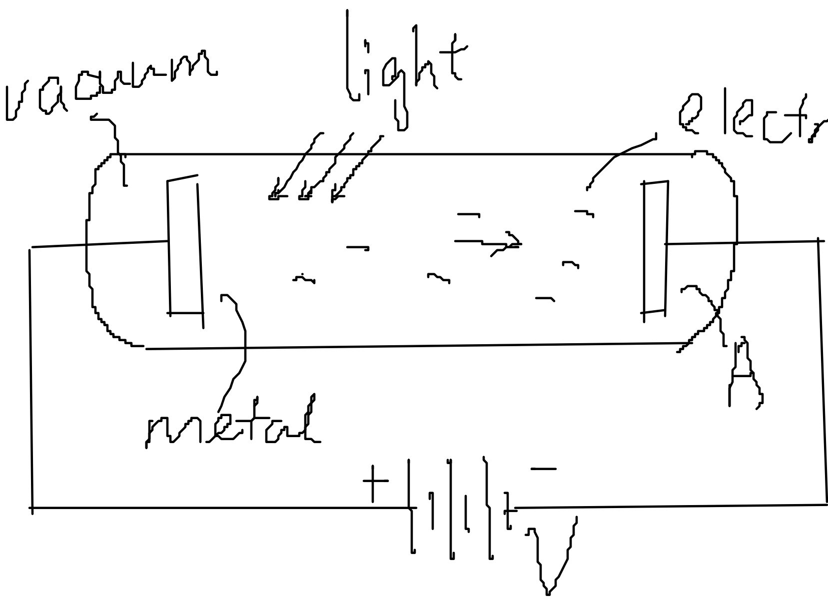
Photon and work function

Dr K M Hock

Photon energy = hf

If absorbed by e^- in metal,

- partly used to overcome attraction from metal ← work function, ϕ
- the rest → $\frac{1}{2}mv_{max}^2$

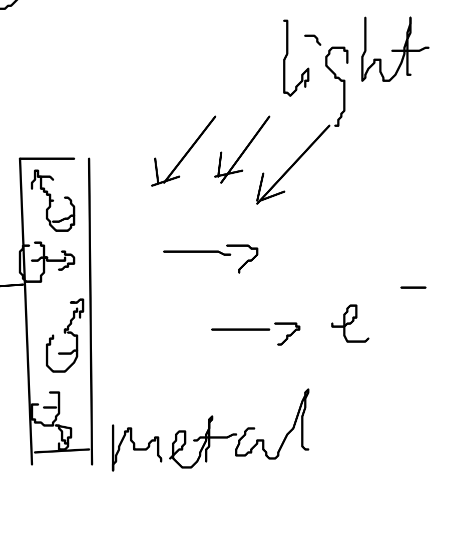


$$hf = \phi + \frac{1}{2}mv_{max}^2$$

Why max?

e^- - random motion in metal

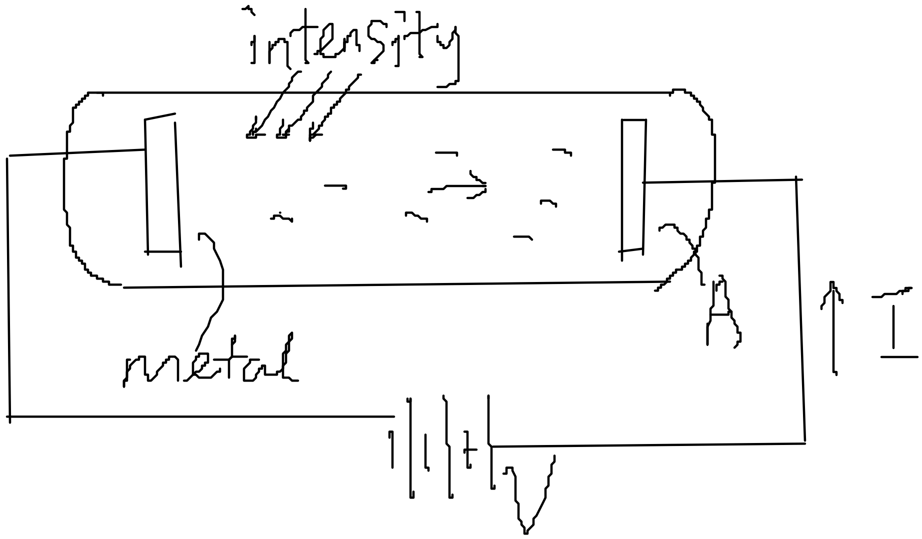
- need different energy to eject
- minimum energy called ϕ
- if needs more, less left for KE
- $\frac{1}{2}m_e v_{max}^2$ for e^- needing least energy.



explain why the maximum photoelectric energy is independent of intensity whereas the photoelectric current is proportional to intensity

Light Intensity and Current

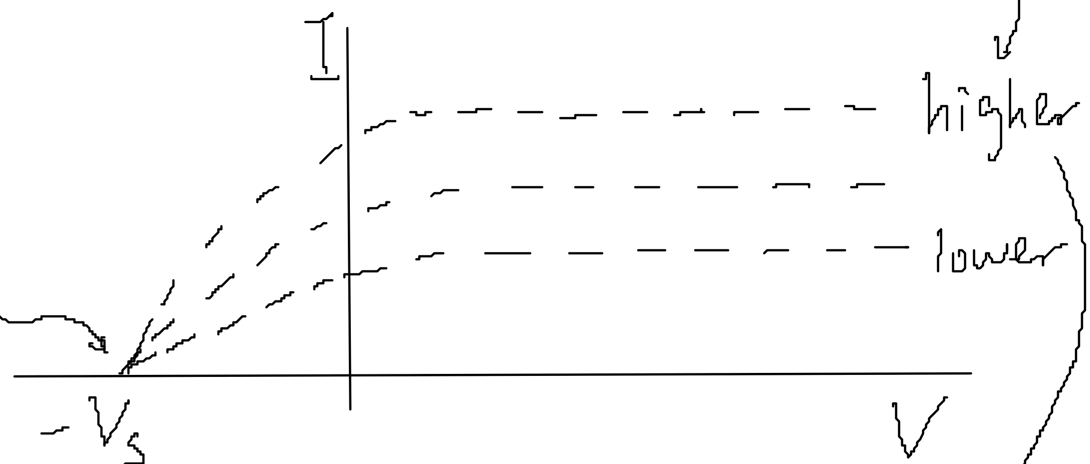
Dr K M Hock



→ Max. photoelectric energy indep. of light intensity.

e^- KE

max $= eV_s$



more photons/s

but electron unlikely to absorb more than 1 photon each time

more e^- absorb photons /s

Photoelectric Current $\propto$ intensity recall, use and explain the significance of hf = Φ + ½mv_max^2

Determining Planck's Constant

Dr K M Hock

$$hf = \Phi + \frac{1}{2} m_e v_{max}^2$$

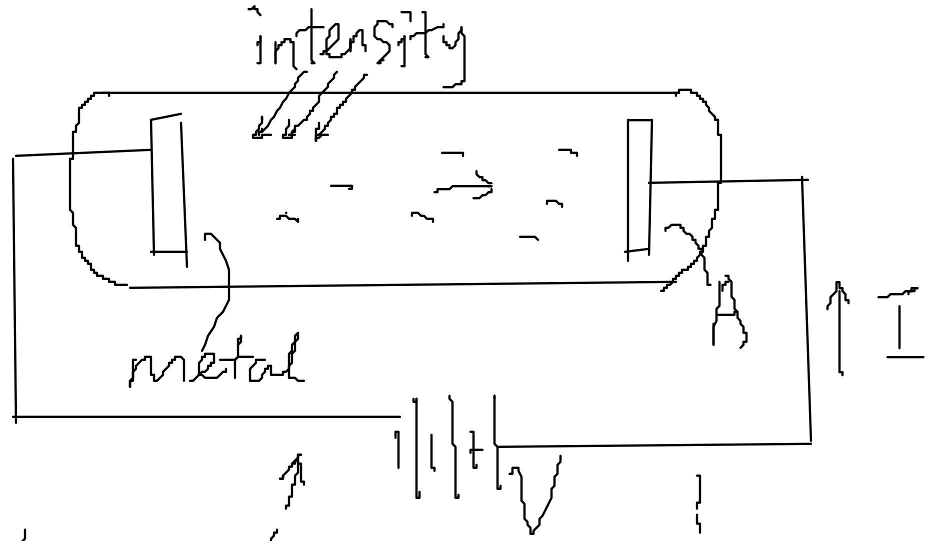
photon energy | work fn to eject e^- | max KE

$$hf = \Phi + eV_s$$

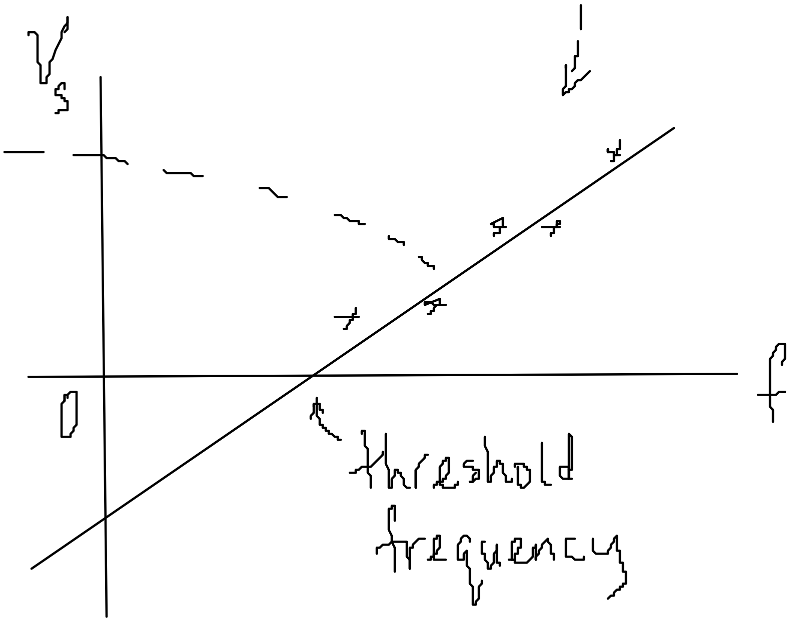
V_s: stopping potential

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

measurement



plot



$$\frac{h}{e} = \text{gradient}$$

find h. (Planck's constant)

describe and interpret qualitatively the evidence provided by electron diffraction for the wave nature of particles

Electron Diffraction

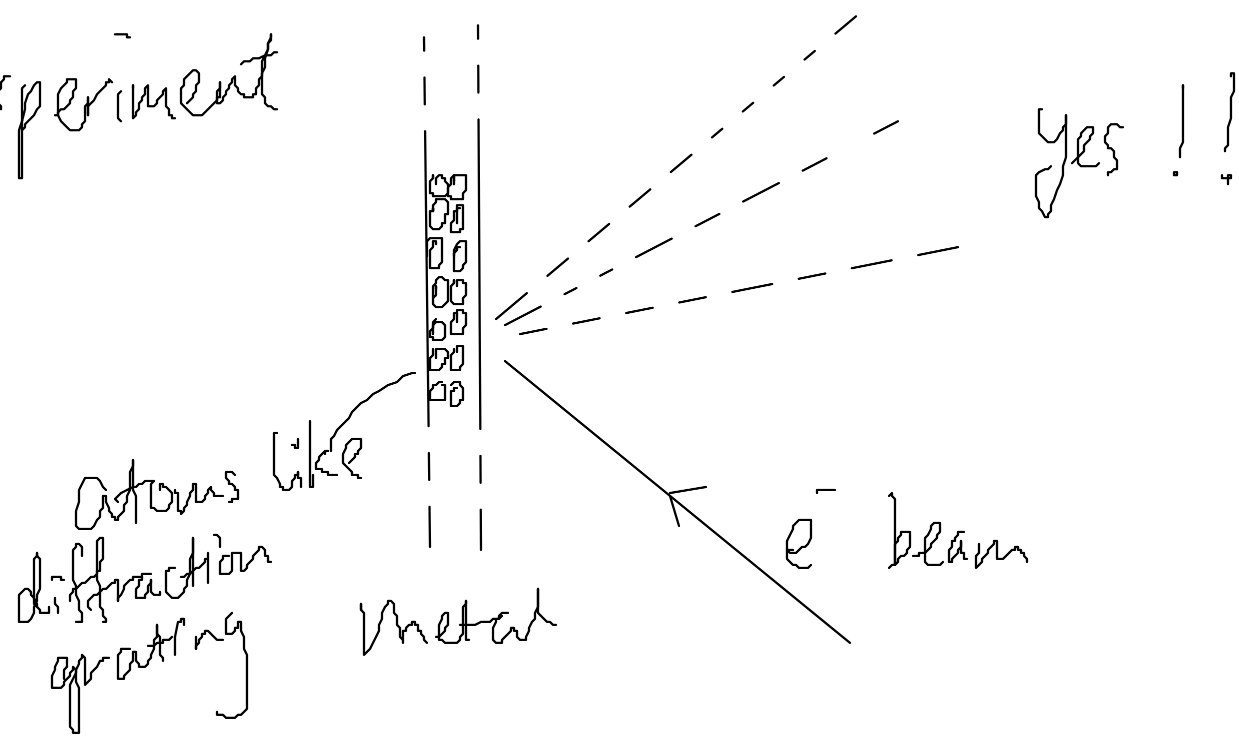
Dr K M Hock

If light wave can behave as particles, Can electron particles behave as waves?

↓

See if e^- can produce interference fringes...

Experiment



de Broglie wavelength

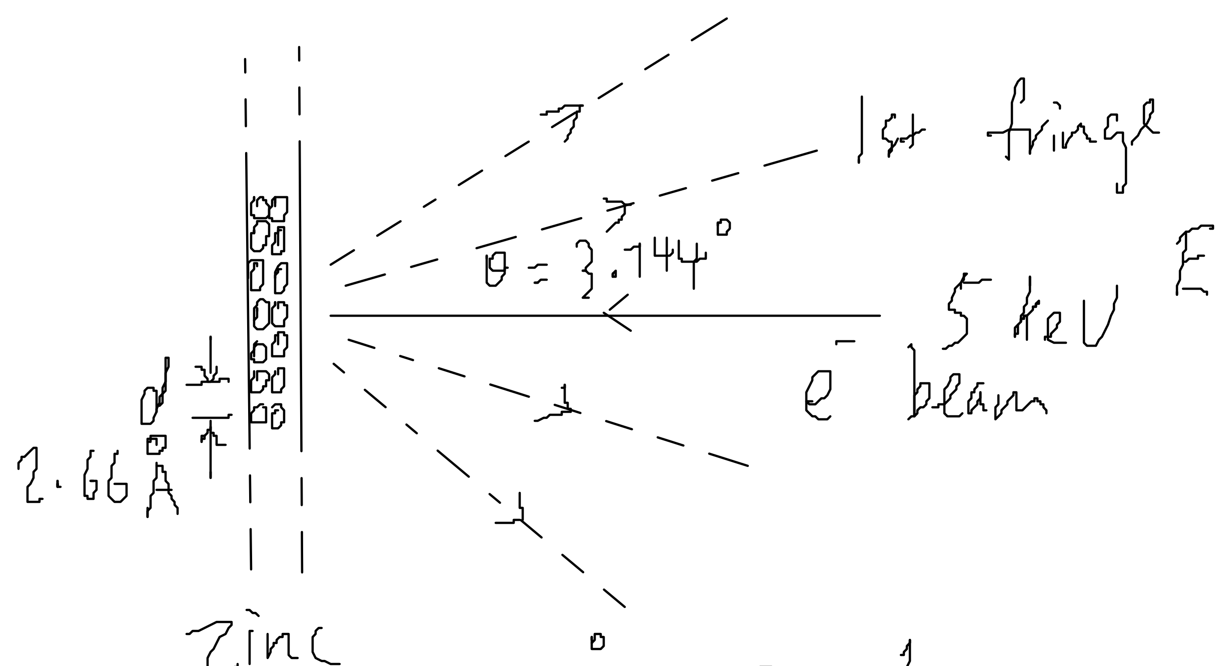
Dr K M Hock

de Broglie suggested that wavelength of a particle is

$$\boxed{\lambda = \frac{h}{p}}$$ ← momentum

Really? – check with experiment.

e.g.



2.66 Å ? 1

Diffraction grating $d \sin\theta = n\lambda$ ← h/p

$\frac{p^2}{2m_e} = E \rightarrow p = \sqrt{2m_eE} = \sqrt{2\times 9.1\times10^{-31}\times5\times10^{3}\times1.6\times10^{-19}}$

$= 3.816\times10^{-23}$ kg m/s

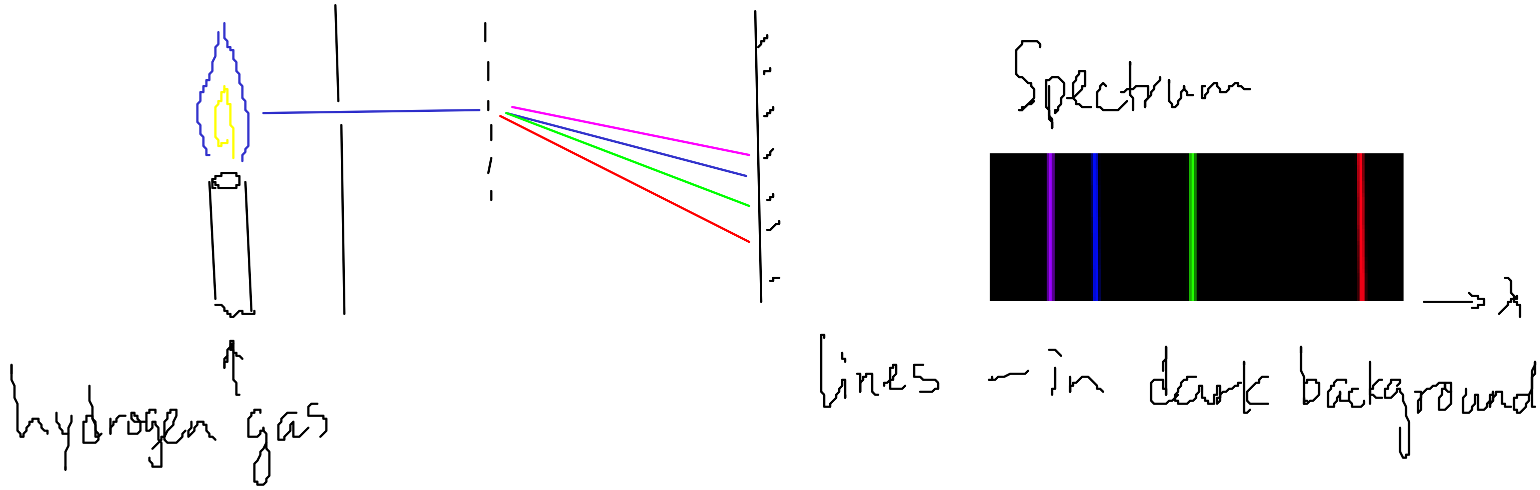
$\lambda = \frac{h}{p} = \frac{6.63\times10^{-34}}{3.816\times10^{-23}} = 0.1737$ Å

$\theta = \sin^{-1}\frac{\lambda}{d} = \sin^{-1}\frac{0.1737}{2.66} = 3.744°$ Yes!

show an understanding of the existence of discrete electron energy levels in isolated atoms (e.g. atomic hydrogen) and deduce how this leads to spectral lines

Spectral Lines and Energy Levels

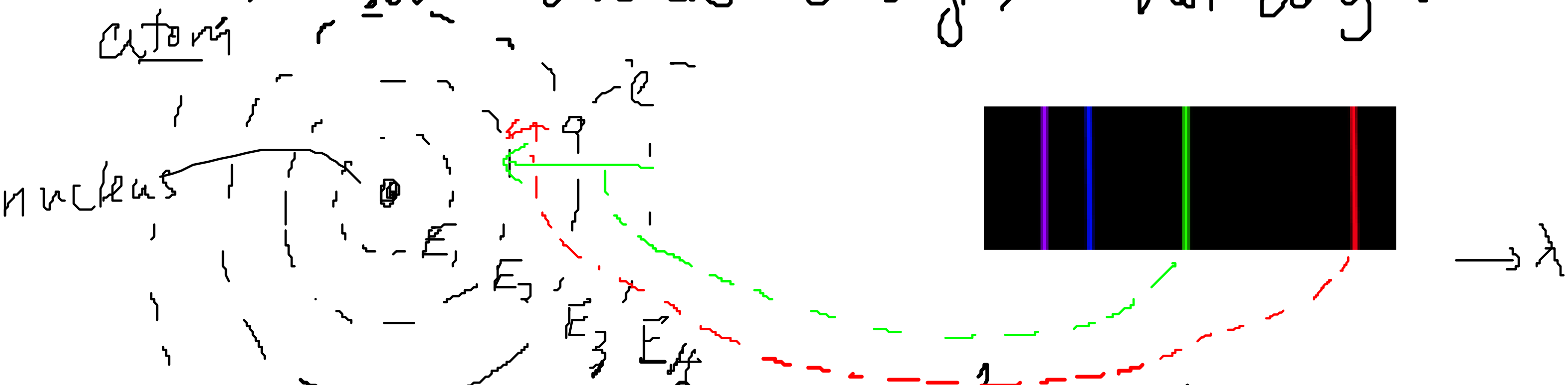
Dr K M Hock



Why not rainbow like Sunlight ??

Niels Bohr suggested :

- maybe e^- in H atom only allowed some discrete energies – not any value



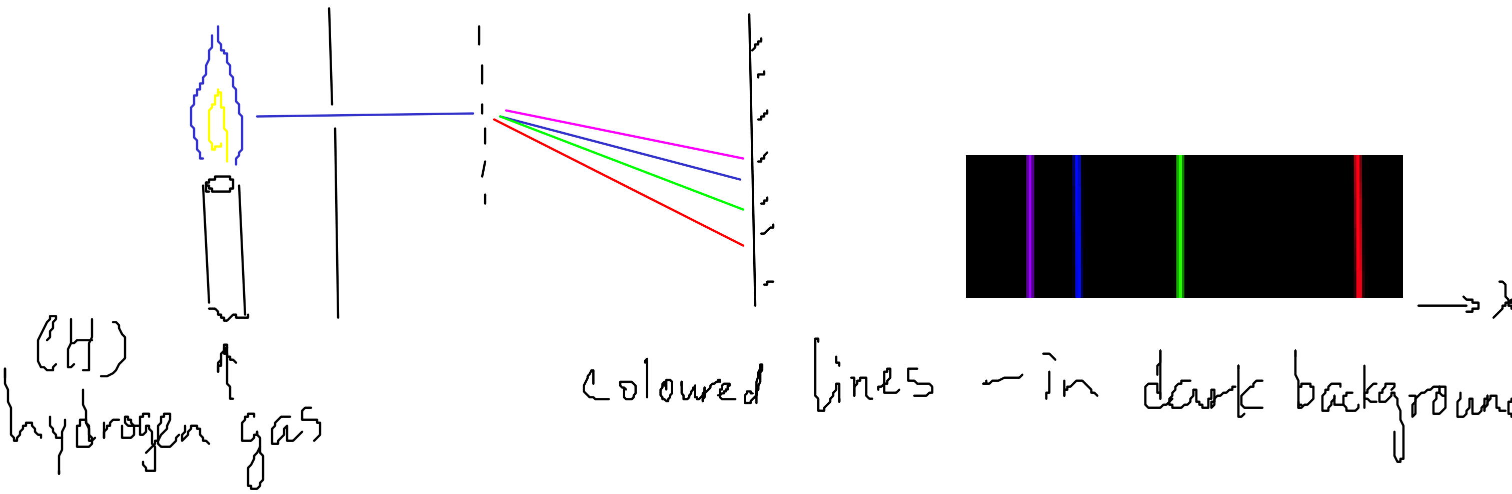
- then if e^- fall from higher to lower energy, they also cannot lose any amount of energy
- this energy loss is converted to light energy
- Since $E = hf$, we can only see certain frequency (colour)

Line Spectrum

Dr K M Hock

Emission line Spectrum

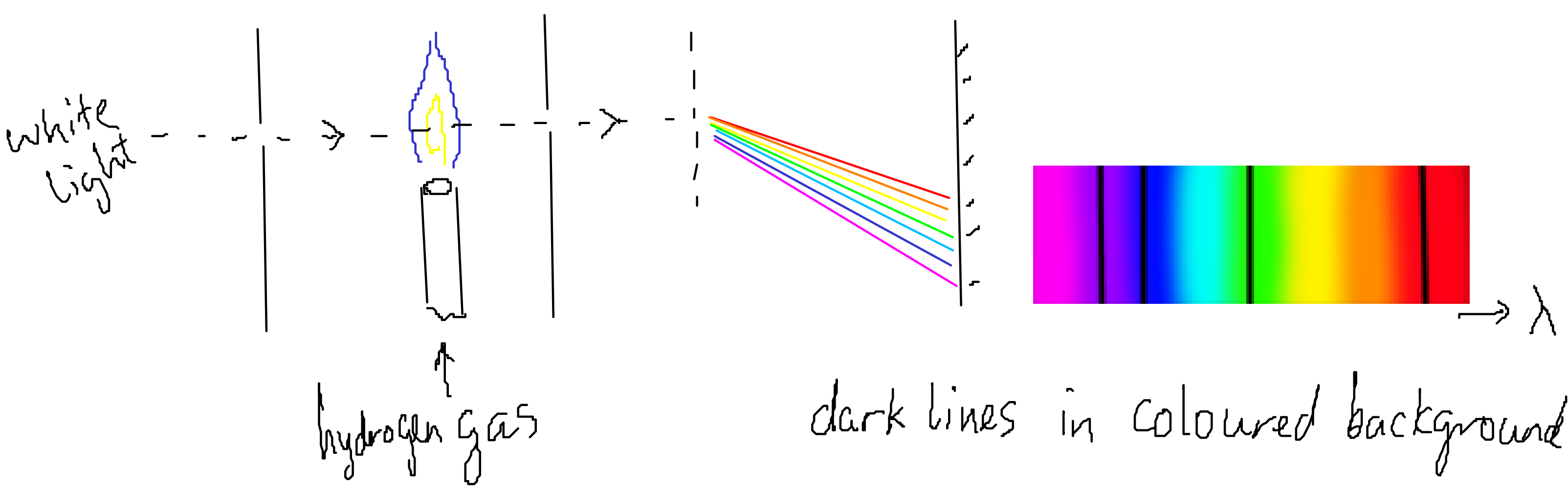
H atoms' e^- excited to higher level by fire.



coloured lines – in dark background

When e^- ↓ lower levels → emits light.

Absorption Line Spectrum

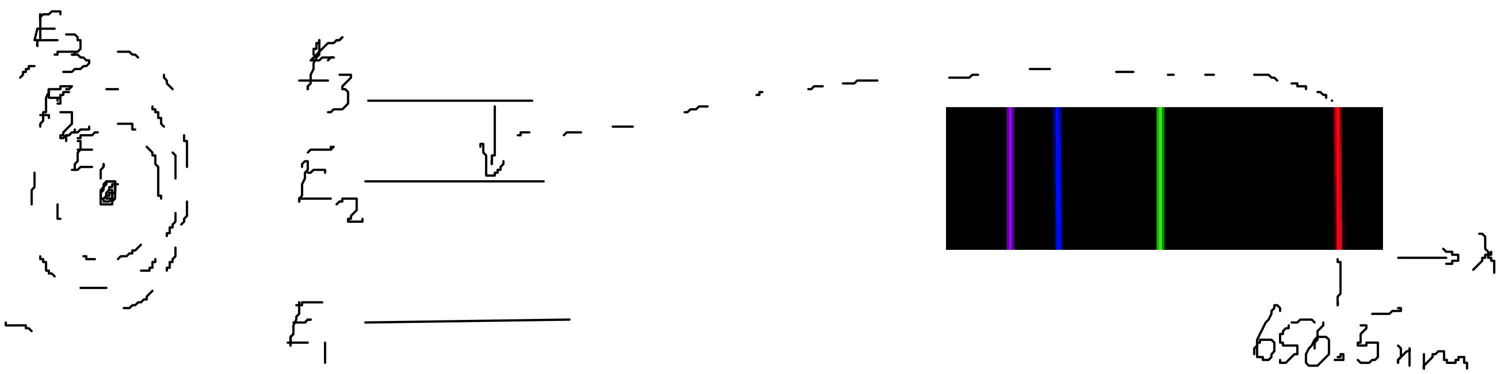


dark lines in coloured background

Because e^- in H atoms can also aborb energy (get excited) from incident light
- and re-emit is all directions.

Emit and Absorb Photons

Dr K M Hock



Q. The transition of an e^- from energy level E_3 to E_2 in H atom emits a photon of wavelength 656.5 nm.
Find the difference between the levels.

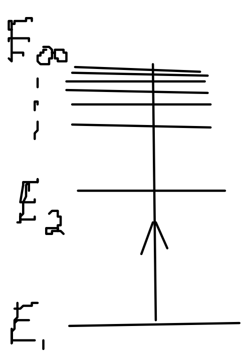
A. $E = hf \rightarrow E_3 - E_2 = hf$

$c = f\lambda \rightarrow f = \frac{c}{\lambda} \rightarrow E_3 - E_2 = \frac{hc}{\lambda}$

$$E_3 - E_2 = \frac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{656.5 \times 10^{-9}}$$

$$= 3.030 \times 10^{-19}\ J$$

Q.



It takes 13.6eV to remove an e^- at ground state from a H atom. What wavelength of photon has this energy?

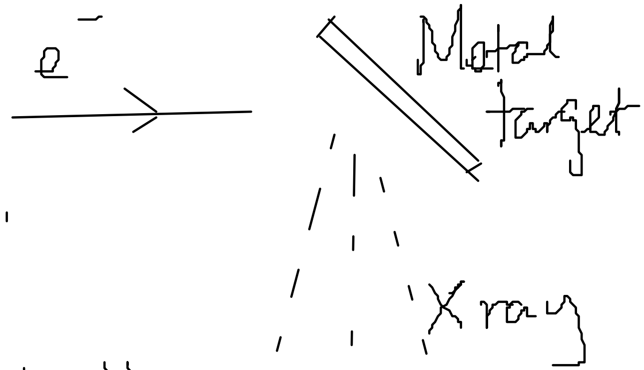
Ans. 91.41 nm

explain the origins of the features of a typical X-ray spectrum using quantum theory

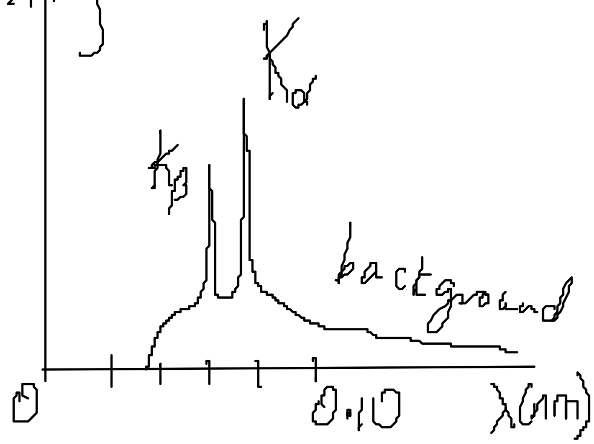
X ray spectrum

Dr K M Hock

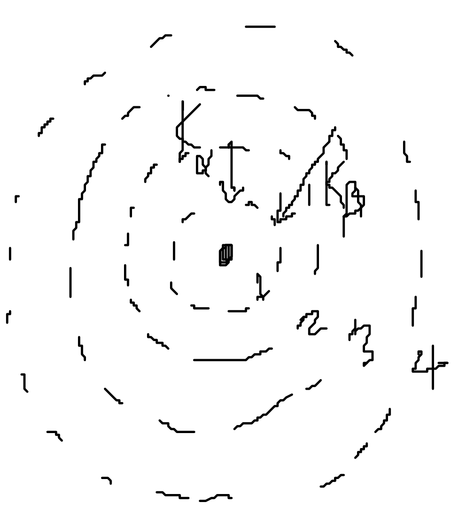
High energy e^- beam hitting a metal → X ray.



Spectrum of this
→ alway 2 peaks for any metal.
- peaks λ always same for same metal
- different for different metal.



e.g. Molybdenum metal (Mo)



Explain - incident e^- removes e^- from inner shells of metal atom

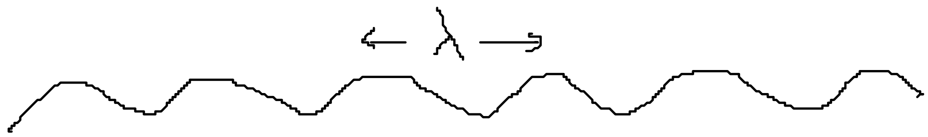
- K_β peak produced by $E_3 \rightarrow E_1$ transition
- K_α : $E_2 \rightarrow E_1$ "

show an understanding of and apply the Heisenberg position-momentum and time-energy uncertainty principles in new situations or to solve related problems

Uncertainty Principle

Dr K M Hock

$p = \frac{h}{\lambda}$



A definite momentum p ⇒ constant λ

⇒ infinitely long wave, look same everywhere

⇒ no idea where particle is

Add a range of λ's:

$p = \frac{h}{\lambda}$ ⇒ range of λ → range of p, Δp.

So $\Delta p \uparrow$, $\Delta x \downarrow$.

Heisenberg discovered: $\Delta p \Delta x \simeq h$.

---

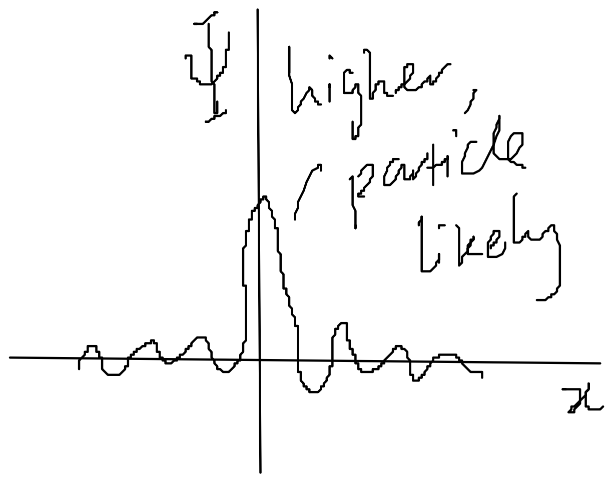
looks like $E = \frac{h}{T}$ ← $E = hf$ (T = period)

So $\Delta E \Delta t \sim h$. – use for spectral line width (ΔE) vs. transition time (Δt)

show an understanding that an electron can be described by a wave function Ψ where the square of the amplitude of wave function I Ψ I^2 gives the probability of finding the electron at a point.

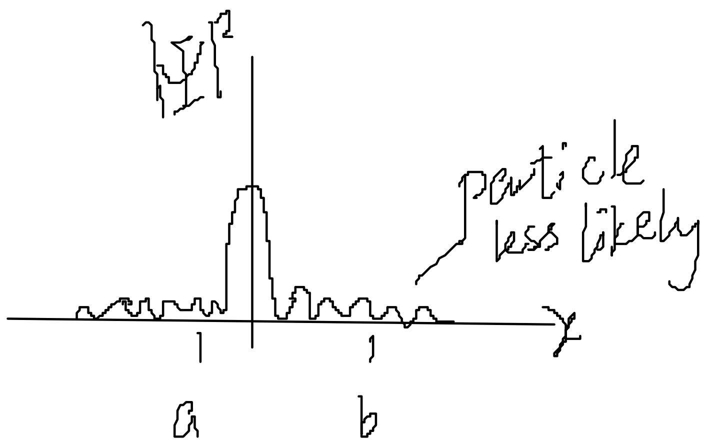
Wave Function

Dr K M Hoc



The wave is called wavefunction.

$|\Psi(x)|^2$ = probability of finding the e^- at x.



To be precise, probability of finding e^- between a and b is area under $|\Psi|^2$ graph between a, b.

So total area under graph = total probability = 1.

show an understanding of the concept of a potential barrier and explain qualitatively the phenomenon of quantum tunnelling of an electron across such a barrier

Quantum Tunnelling

Dr K M Hoc

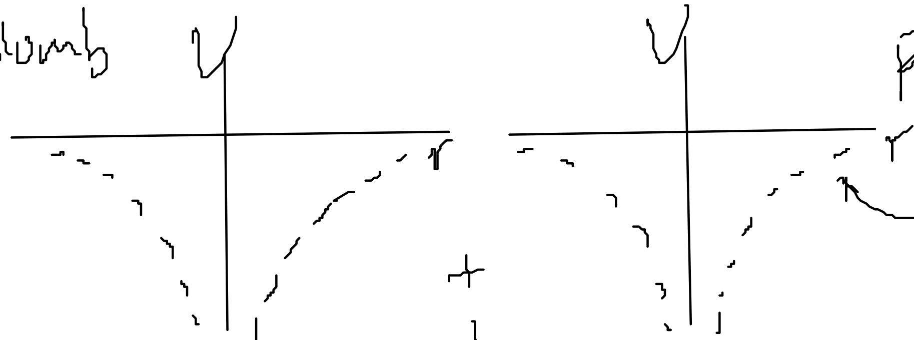
If $\frac{1}{2}mv^2 < mgh$,

not enough KE to overcome potential energy

potential barrier.

Atoms:

Coulomb



potential $-\frac{Q}{4\pi\varepsilon_0 r}$

Combine:

potential barrier

e^- not enough KE to overcome potential.

but because e^- is a wave, wave can spread into barrier.

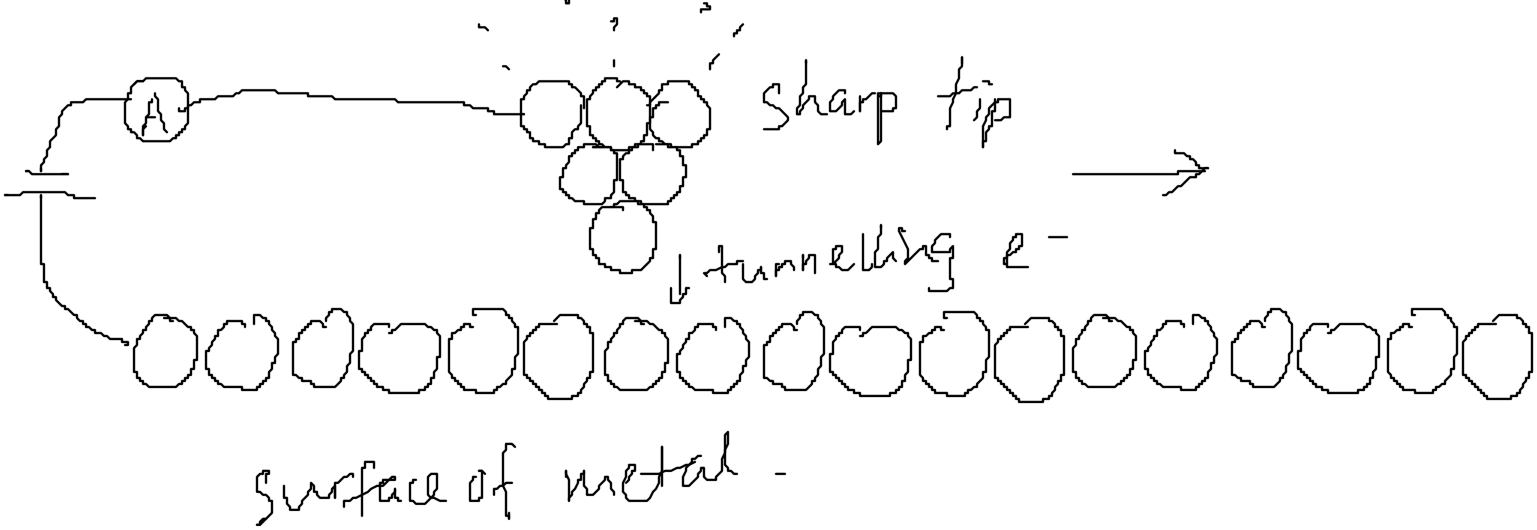
If barrier not too high or wide, e^- can "tunnel" through!

describe the application of quantum tunnelling to the probing tip of a scanning tunnelling microscope (STM) and how this is used to obtain atomic-scale images of surfaces.

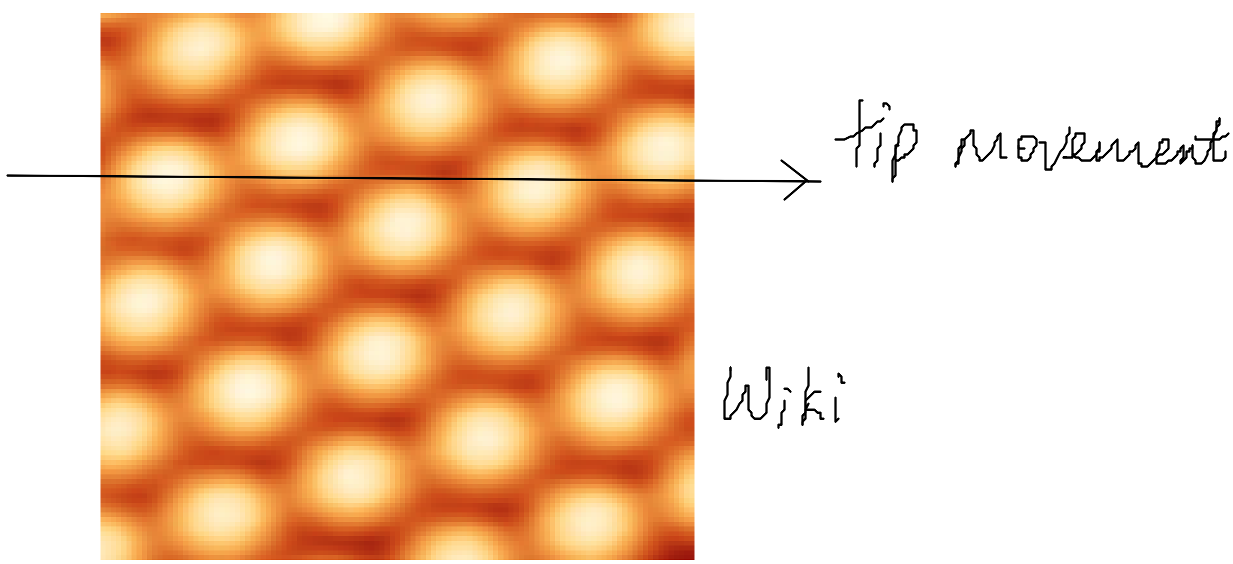
Scanning Tunnelling Microscope

Dr K M Hock

Can we see atoms?



When a sharp tip is moved over a surface, tunnelling current changes with its spacing from surface atoms.



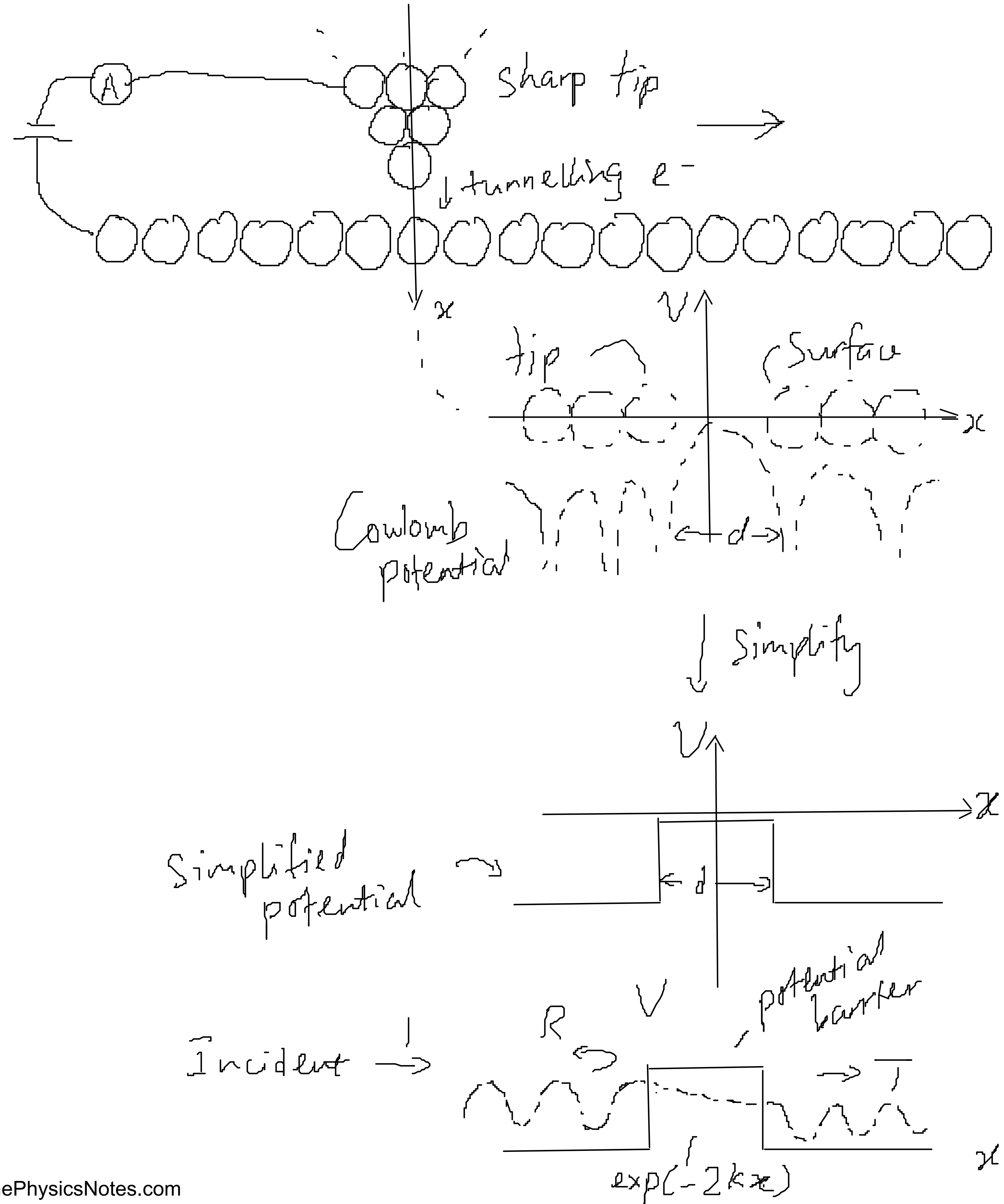
Wiki

Plotting a graph of the currents gives image of atoms!

apply the relationship transmission coefficient T proportional to exp(-2kd) for the STM in related situations or to solve problems.

Transmission Coefficient

Dr K M Hock

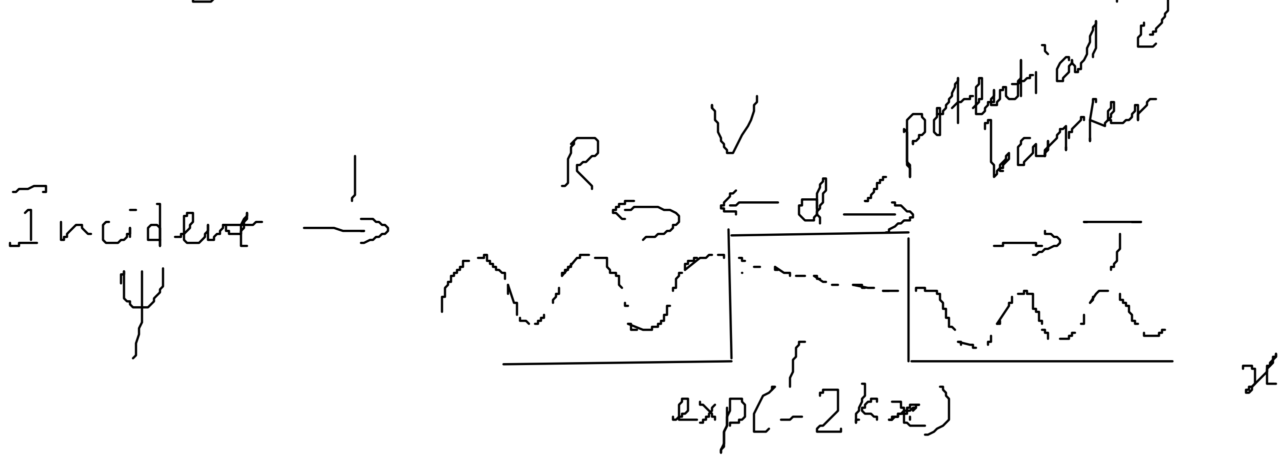


recall and use the relationship R + T = 1, where R is the reflection coefficient and T is the transmission coefficient, in related situations or to solve problems.

Reflection Coefficient

Dr K M Hock

Electron wave can tunnel thru' a



In the barrier, wave → exponential

When it tunnels thru'; amplitude → $\exp(-2kd)$ × incident amplitude ψ

d = width of barrier.

Since $|\psi|^2 \sim$ probability, →

→ some e^- transmitted (T)

→ some reflected (R)

$1 = R + T$ — transmission coefficient ~ probability

(R: reflection coefficient ~ probability)