Waves and diffraction

Matthew Edmonds

Thursday 14th July 2016

GCSE enrichment week 2016

Overview – What are we going to learn?

- We saw before that light can behave as a particle.
- Can matter particles also behave as waves?
- Classical particles are reflected from surfaces just like quantum particles, so this does not tell us if something is a wave or particle.
- Diffraction and Interference are unique to waves!

Historical perspective

- Building on Einstein's earlier work, *de Broglie* asked if particles can have wave properties

- In his PhD thesis, he defined a wavelength for matter.

- The de Broglie wavelength tells us the scale over which the wave properties of matter manifest.

Historical perspective

- The de Broglie hypothesis was confirmed by **Davison** and **Germer**.
- They directed an electron beam at a Nickel target.
- They saw a diffraction pattern – showing matter can show wave properties.

What is diffraction?

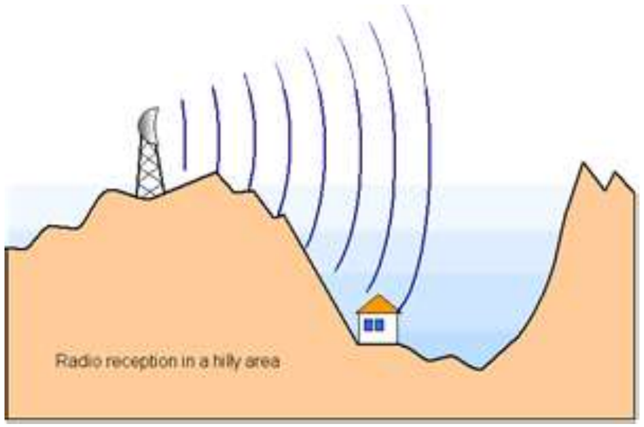
- Diffraction is the property of waves.
- Every wave has a wavelength – the constant distance between each peak.
- If a wave interacts with an object similar in size to its wavelength, diffraction can occur.
- Many different physical systems show this behaviour!

Where can we see diffraction?

Water waves
in a harbour

Light incident on
an optical disk

Radio waves
in valleys



When can diffraction occur?

- Matter has a wavelength shown by de Broglie to be:

Planck's constant

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

Velocity

Wavelength

Mass

Can a Human being show diffraction?

- To understand if a person can show wave properties, we can calculate their de Broglie wavelength.

- Assume mass of one person is 70 kg, with a velocity of 1 ms^{-1}

$$\lambda_{\text{human}} = \frac{h}{mv} = 10^{-35} \text{ m}$$

- This is a *tiny* distance! Everyday objects do not show wave behaviour!

Example 3 – The electrons wavelength

Question: *What is the wavelength of an electron with velocity 7,000 km s^{-1}*? [the electron mass m_e=9.11x10^{-31} Kg]

Answer: The de Broglie wavelength is $\lambda = h/mv$.

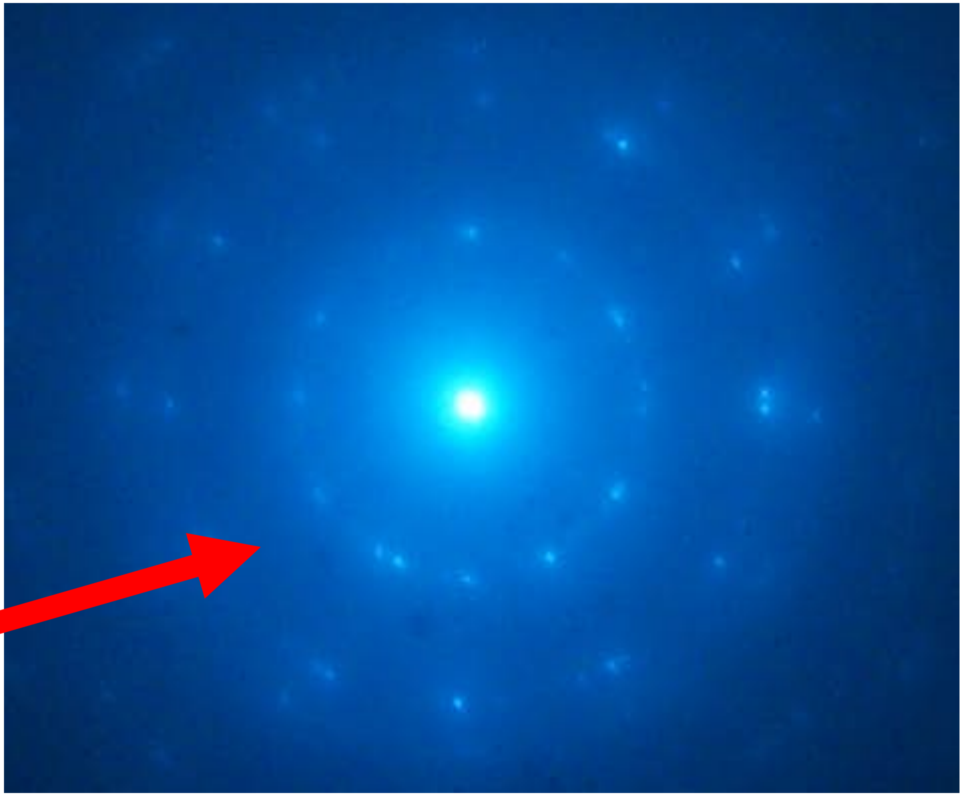
Then: λ = 6.63x10^{-34}J s/(9.11x10^{-31} Kg x 7x10^{6} m s^{-1})

= 10^{-10} m (or 0.1 nm)

Electron diffraction

- Electrons show diffraction effects when incident on solids
- Spacing of atoms in solids is similar to the electrons wavelength

Diffraction pattern can be used to understand the properties of solids

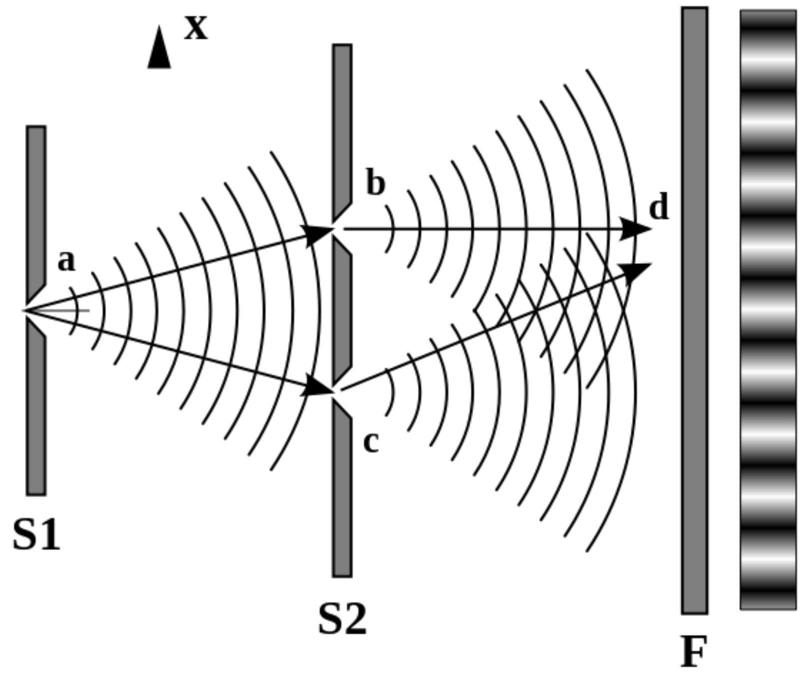


Young’s double slit experiment

- Young (1773-1829) was a polymath who made notable contributions to mathematics, physics, medicine, music and even Egyptology!
- Remembered for *Young’s slit experiment.*
- Young’s theory initially met with hostility
- Eventually accepted, a direct demonstration of the wave nature of light.

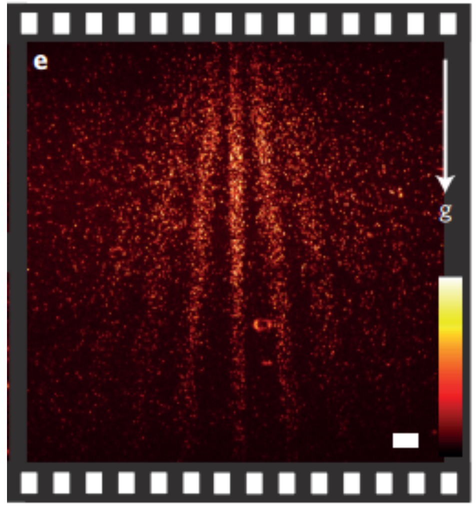
Young’s double slit experiment

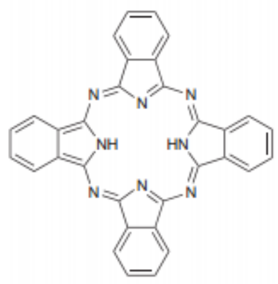
- Pass a light source through a single and then a double slit
- A diffraction pattern is seen on the screen
- This idea can also be used to show the diffraction of matter waves



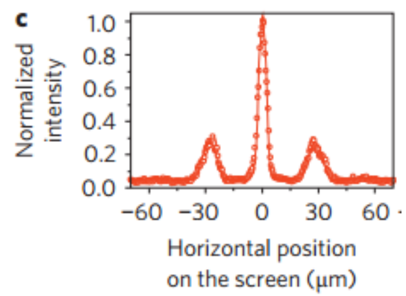
Young's double slit experiment

- If atoms can show wave-like properties, how big can we make the diffracted object?
- Researchers showed that molecules made from > 100 atoms can diffract!
- The diffraction patterns and molecular structure are shown.

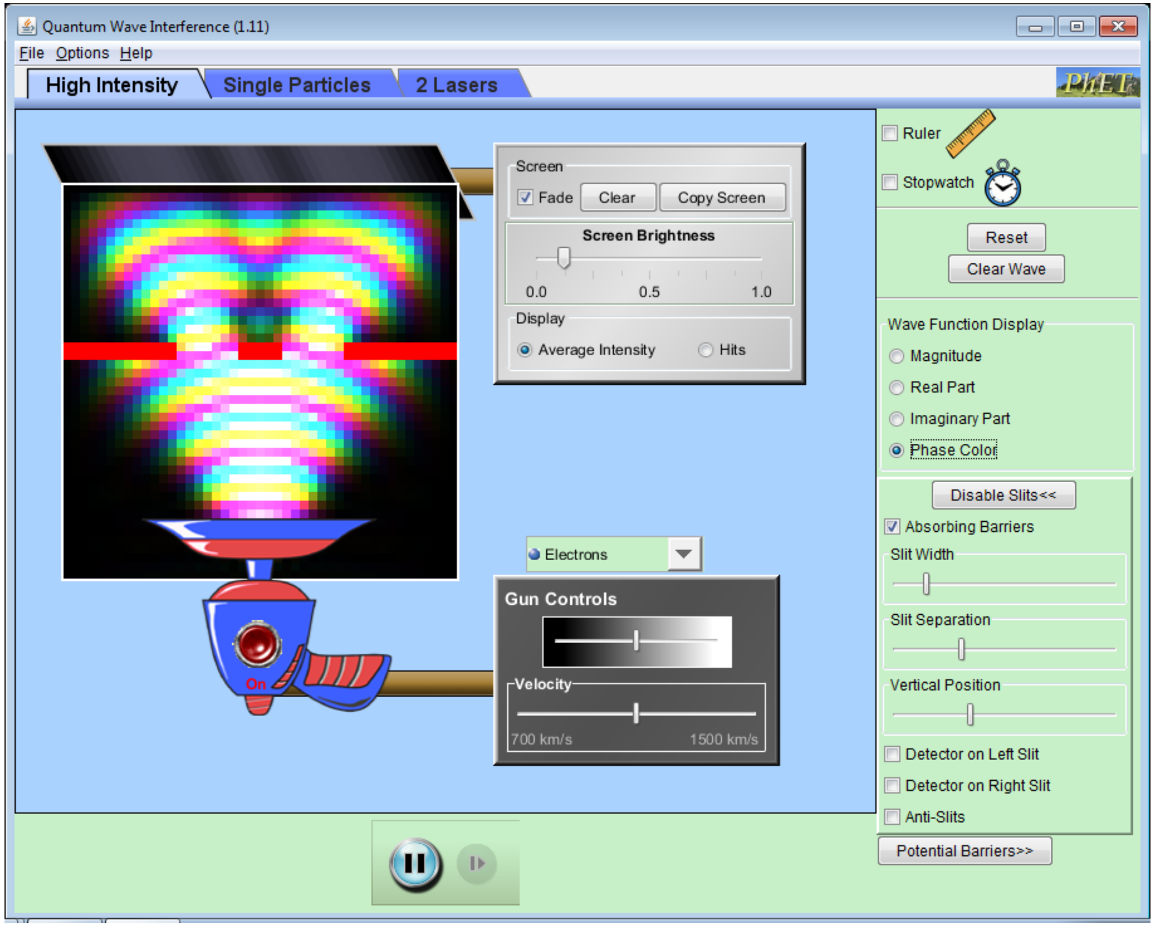




PcH_2



Activity 2 – *Quantum Wave Interference*



Classical versus Quantum descriptions

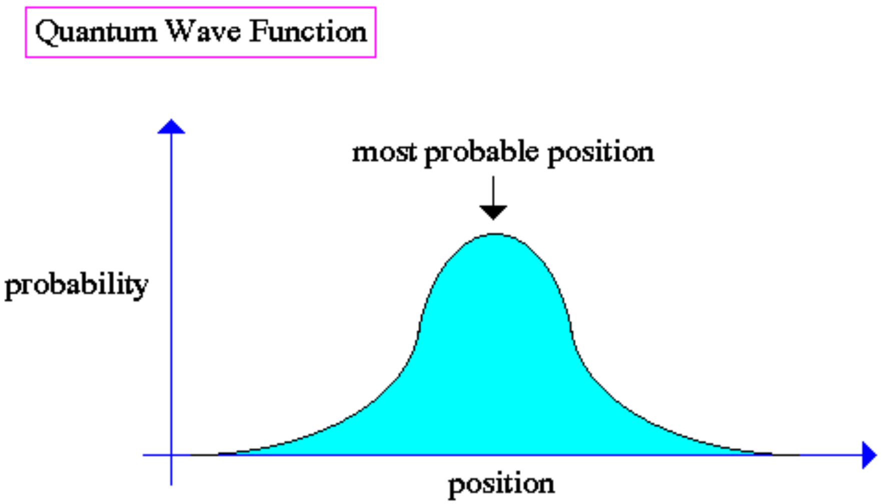
- Classical mechanics tells us that if we know the forces acting on a system at some time, we can know the trajectories for all time
- Not so with quantum systems!
- The *Uncertainty principle* tells us that the more information we have about one observable quantity, the less we will have about another!

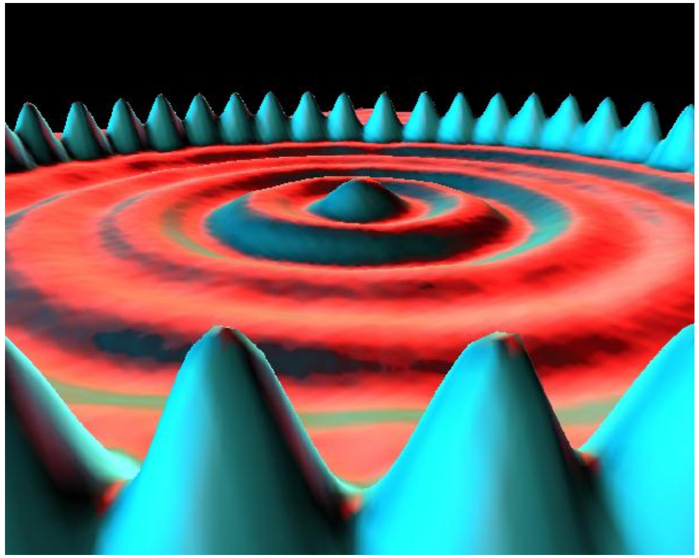
The Uncertainty Principle

- Werner Heisenberg (1901-1976), theoretical physicist
- Pioneer of quantum mechanics, theory of how atoms and light behave
- Awarded Nobel prize for contributions to quantum theory

The Uncertainty Principle

- Quantum particles are described in terms of a wave function, **Ψ**.
- Quantum particles properties are computed using this **Ψ**.





The Uncertainty Principle

- Each wave function **Ψ** has an Uncertainty associated with it
- A measure of how ‘spread’ the waves that make up **Ψ** are.

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

Planck’s constant

Uncertainty in position

Uncertainty in momentum

Exercise 4 - Uncertainty

Question: A certain quantum particle has a mass *m*=1.6x10^{-27} Kg and an uncertainty in position of $0.1\text{n}m$. What is the *minimum* uncertainty in it's velocity?

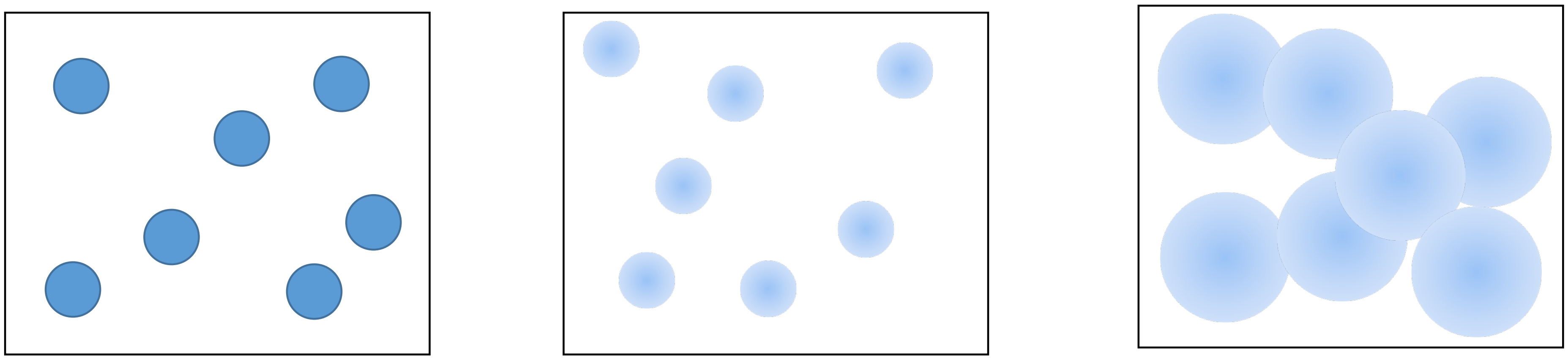
Answer: The minimum uncertainty occurs when $\Delta x \Delta p = h/4\pi$.

So we have $\Delta p = \frac{h}{4\pi\Delta x}$ = 5.3 x 10^{-25} Kg m s^{-1}

then since $\Delta p = m\Delta v$, we find $\Delta v = \frac{\Delta p}{m}$ = <u>330 ms^{-1}</u>

Quantum Mechanics near absolute zero

- Possible to prepare gases of trapped atoms close to zero temperature

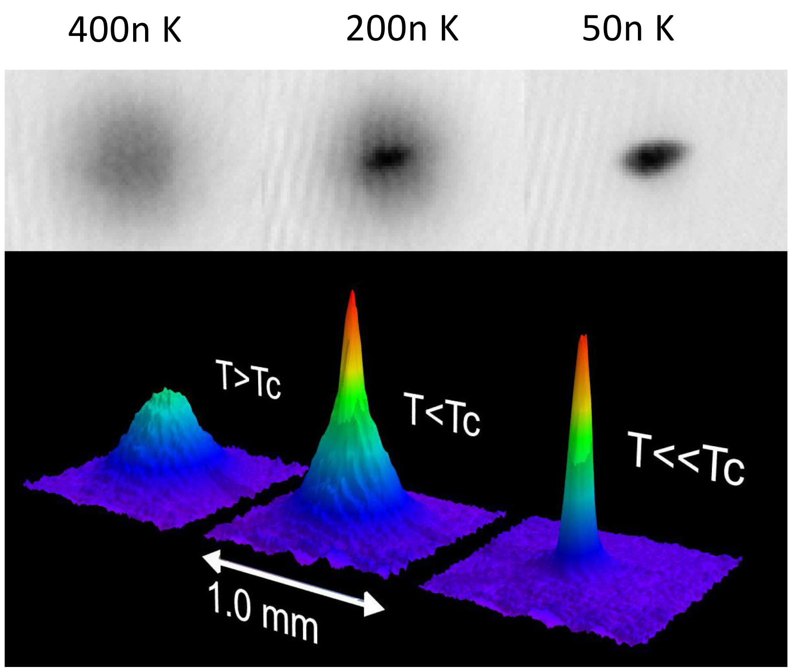


$T > T_c$ $\quad$ $T \sim T_c$ $\quad$ $T << T_c$

- High temperature: classical behaviour, Low temperature: blurry quantumness!

Bose-Einstein condensation

- By carefully cooling atoms down to temperatures close to absolute zero, a new form of matter was created in 1995
- Giant matter wave of atoms formed with Rubidium gases
- Created in over one hundred labs all over the world, nearest is Durham.



Summary

- Matter can behave as a wave as well as a particle.
- The double slit experiment has been used to demonstrate this.
- Quantum matter is described a wave function $\boldsymbol{\Psi}$.
- Quantum mechanics tells us that there is an *uncertainty* in quantities like position and momentum.