- ***Candidates should be able to*** *:*
  - ***Explain electron diffraction*** *as evidence for the wave nature of particles like electrons.*
  - ***Explain*** *that electrons travelling through polycrystalline graphite will be diffracted by the atoms and the spacing between the atoms.*
  - *Select and apply the* ***de Broglie*** *equation :* $\boxed{\lambda = \frac{h}{mv}}$
  - ***Explain*** *that the diffraction of electrons by matter can be used to* ***determine the arrangement of atoms*** *and the* ***size of nuclei.***

WAVE-PARTICLE DUALITY OF LIGHT

The phenomena of ***reflection, refraction, interference and diffraction*** *can all be explained using the idea of light as a* ***wave motion.*** *Furthermore, the fact that light can be polarised indicates that the waves are* ***transverse.***

The ***photoelectric effect*** *however, requires an explanation which considers light and all other electromagnetic radiation as a particle motion (i.e. consisting of discrete packets of energy called* ***photons****).*

*These two, sharply contrasting ideas (****wave*** *and* ***particle****) are just different models which we use to aid our explanations for the behaviour of electromagnetic radiation in different circumstances.*

So light, and all electromagnetic radiation can be thought of as a ***wave*** *or a* ***particle*** *depending on which phenomenon we want to explain.*

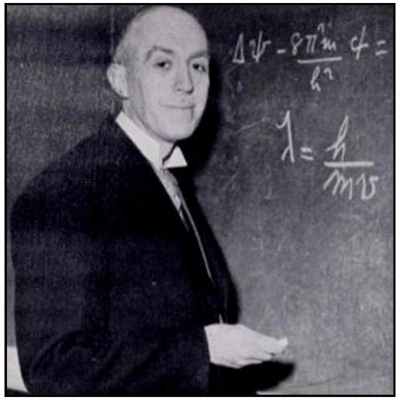
SUMMARY

All electromagnetic radiation can be thought to have :

- *A* ***WAVE*** *nature and phenomena such as* ***interference, diffraction and polarisation*** *provide evidence in favour of this model.*
- *A* ***PARTICLE*** *nature and the* ***photoelectric effect*** *and the existence of* ***line spectra*** *provide evidence in favour of this model.*

WAVE-PARTICLE DUALITY OF MATTER

Based on the idea that light and all other electromagnetic Radiation may be considered a particle or a wave nature, ***Louis de Broglie*** *suggested that the same kind of duality must be applicable to matter.*



He proposed that any particle of matter having ***momentum (p)*** *Has an associated* ***wavelength (λ)*** *given by :*

(J s)

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

(m) (kg m s^{-1}) (kg) (m s^{-1})

m = particle mass
v = particle velocity

λ' Is also known as the de Broglie wavelength.

NOTE

- *All physical entities can be described as **waves** or **particles**. The two models are linked by the following relationships :*

*These two quantities are linked to a **PARTICLE** description.*

$$E = hf$$

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

*These two quantities are linked to a **WAVE** description.*

- *Consider an electron of **mass (m)** and **charge (e)**, Accelerated from **rest** to a **final velocity (v)** by a **pd (V)**. Then :*

Kinetic energy gained by electron = work done by the accelerating pd

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

$$v = \sqrt{(2eV/m)}$$

*So, by accelerating charged particles to higher and higher velocities, we can make their momentum greater and greater and since $\lambda = h/p$, this will make their **de Broglie wavelength** (λ) shorter and shorter.*

- PRACTICE QUESTIONS (planck's constant, h = **6.63 x 10-34 J**)

1 Calculate the **de Broglie wavelength** associated with each of the following :

(a) A bullet of mass **25 g** moving at a velocity of **280 m s^{-1}**.

(b) An sprinter of mass **90 kg** moving at a velocity of **11 m s^{-1}**.

(c) An electron of mass **9.11 x 10^{-31} kg** moving at a velocity of **2.0 x 10^{7} m s^{-1}**.

2 Calculate the **momentum** and **velocity** of :

(a) An electron having a de Broglie wavelength of **2.0 x 10^{-9} m**.

(b) A proton of mass **1.67 x 10^{-27} kg** and a de Broglie wavelength of **5.0 nm**.

3 Calculate the associated **de Broglie wavelength** of the electrons in an electron beam which has been accelerated through a pd of **4000 V**.

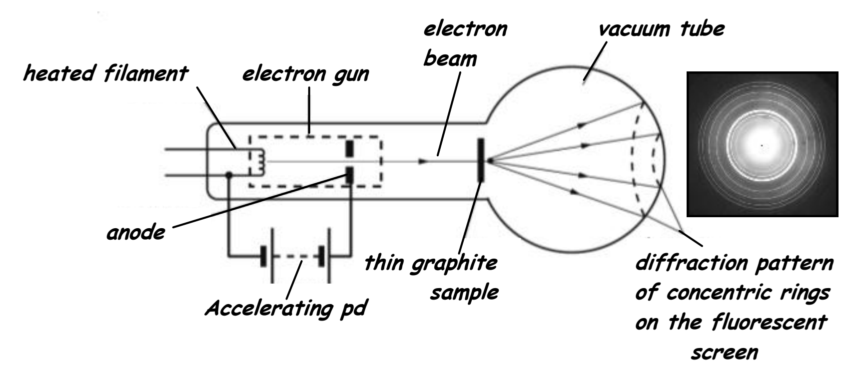
Electron charge, e = **- 1.6 x 10^{-19} C**.
Electron mass, m = **9.11 x 10^{-31} kg**.

4 An alpha particle emitted from a radon-220 nucleus is found to have a de Broglie wavelength of **5.7 x 10^{-15} m**. Use the following data to calculate the **energy** of the alpha particle **in MeV**.

Electron charge, e = **- 1.6 x 10^{-19} C**.
Alpha particle mass, m_α = **6.7 x 10^{-27} kg**.

• ELECTRON DIFFRACTION

In 1927, ***Davisson & Germer*** *showed that electrons were diffracted after passing through single nickel crystals. In the same year* ***George Thomson*** *achieved a similar result when he directed a high energy electron beam at a thin metal foil in a vacuum tube. These two milestone experiments provided the evidence which confirmed* ***de Broglie's*** *suggestion that electrons could exhibit* ***wave*** *behaviour.*



The apparatus shown above is used to demonstrate electron diffraction.

The electrons are emitted from a heated filament cathode and they are accelerated to high velocities by the large positive pd between the anode and cathode.

The ***polycrystalline*** *graphite sample is made up of many tiny crystals, each consisting of a large number of regularly arranged carbon atoms.*

The electrons pass through the graphite and produce a diffraction pattern of concentric rings on the tube's fluorescent screen. The ***de Broglie wavelength*** *of the electrons is of the* ***same order of magnitude*** *as the* ***spacing between the carbon atoms,*** *so this acts like a diffraction grating to the electrons.*

Diffraction is a ***wave*** *phenomenon and since these electron diffraction rings are very similar to those obtained when light passes through a small, circular aperture, they provide strong evidence for the* ***wave behaviour of matter proposed by de Broglie.***

It should also be noted that the image seen on the fluorescent screen is due to the individual light flashes produced as each electron strikes the screen. In this respect, the electrons are exhibiting ***particle behaviour.***

USING ELECTRON DIFFRACTION TO STUDY THE STRUCTURE OF MATTER

- *Information about the way in which atoms are arranged in a metal can be obtained by studying the patterns produced when relatively slow-moving ($v \approx 10^{7}$ m s^{-1}) are diffracted after passing through a thin sample. The photograph opposite shows a typical electron diffraction pattern.*

- *Diffraction effects are most significant when the wavelength of the incident radiation is of the same order of magnitude as the gap or ostacle. This also applies to electron diffraction, but in this case we are dealing with the de Broglie wavelength.*
  The separation of atoms in a metal is ~10^{-10} m, so the diffracting electrons must be accelerated to a speed which will give them a de Broglie wavelength of ~10^{-10} m

- Calculate the speed at which the electrons must be moving in order to have a de Broglie wavelength of 10^{-10} m.

- Calculate the accelerating pd needed to give the electrons the speed you have calculated above.

USING ELECTRON DIFFRACTION TO ESTIMATE NUCLEAR DIAMETER

Matter can be probed more deeply by using waves of ***even shorter wavelength.*** *Electrons accelerated to high energies of ~* ***1 GeV*** *have a de Broglie wavelength of ~* ***10^{-15} m.*** *When a narrow beam of such electrons is directed at a metal target, the nuclei of the metal atoms diffract the electron waves and the angle of the first diffraction minimum is used to estimate the diameter of the nucleus. This gives a value of around* ***10^{-15} m.***

Very high energy electrons ***(~ 10 GeV)*** *can be used to probe even more deeply into the structure of matter and so reveal the* ***quark*** *structure of protons and neutrons.*

1 (a) The table below shows four statements that may or may not be true about the wave nature of the electron. Place a **tick** next to the statement if it is **correct** and a **cross** if it is **incorrect.**

Electrons can be diffracted by matter. This confirms their wave nature	
The wavelength of the electron is given by the de Broglie equation	
The wave associated with a moving electron is an electromagnetic wave	
The kinetic energy of the electron is given by the equation E = hf	

(b) Calculate the speed of a carbon atom of mass **2.0×10^{-26} kg** travelling in space with a de Broglie wavelength of **6.8×10^{-26} m.**

(OCR AS Physics - Module 2822 - June 2006)

2 In 1924, **Prince Louis de Broglie** suggested that all moving particles demonstrate **wave-like** behaviour.

(a) **State** the de Broglie equation and **define** all the symbols.

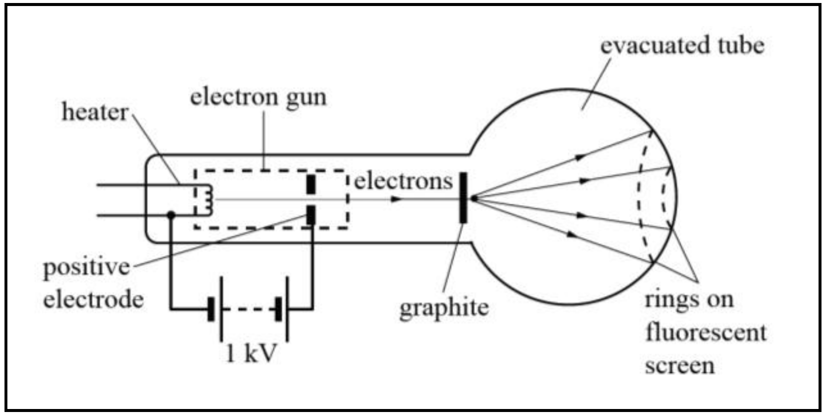
(b) Neutrons may be used to study the atomic structure of matter. diffraction effects are noticeable when the de Broglie wavelength of the neutrons is comparable to the spacing between the atoms. This spacing is typically **2.6×10^{-10} m.**

(i) Suggest why using neutrons may be preferable to using electrons when investigating matter.

(ii) Calculate the speed (v) of a neutron having a de Broglie Wavelength of **2.6×10^{-10} m.** The mass of a neutron is **1.7×10^{-27} kg.**

(OCR AS Physics - Module 2822 - June 2003)

3 Wave-particle duality suggests that an electron can exhibit both **particle-like** and **wave-like** properties.
The diagram below shows the key features of an experiment to demonstrate the **wave-like** behaviour of electrons.



The electrons are accelerated to high speeds by the electron gun. These high speed electrons pass through a thin layer of graphite (carbon atoms) and emerge to produce rings on the fluorescent screen.

(a) Use the ideas developed by de Broglie to **explain** how the experiment demonstrates the **wave-like** nature of electrons.

Suggest what happens to the appearance of the rings when the speed of the electrons is **increased.**

(b) Suggest how, within the electron gun, this experiment provides evidence for the **particle-like** property of the electrons.

(OCR AS Physics - Module 2822 - January 2005)