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:

\[ \lambda = \frac{h}{mv} \]

- 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 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 \( \lambda \) given by:

\[ \lambda = \frac{h}{p} = \frac{h}{mv} \]

Where:
- \( m \) = particle mass
- \( v \) = particle velocity

\( \lambda' \) is also known as the de Broglie wavelength.

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.
**Wave-particle Duality**

**NOTE**

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

  \[ E = hf \]

  \[ p = \frac{h}{\lambda} \]

These two quantities are linked to a PARTICLE description.

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:

  \[ \text{Kinetic energy gained} = \text{work done by the accelerating pd} \]

  \[ \frac{1}{2}mv^2 = eV \]

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

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

**PRACTICE QUESTIONS**

(Planck's constant, \( h = 6.63 \times 10^{-34} \text{ J} \cdot \text{s} \))

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 \times 10^{-31} \text{ kg} moving at a velocity of 2.0 \times 10^7 \text{ m s}^{-1}.

2. Calculate the momentum and velocity of:

   (a) An electron having a de Broglie wavelength of 2.0 \times 10^{-9} \text{ m}.

   (b) A proton of mass 1.67 \times 10^{-27} \text{ 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, \( e = -1.6 \times 10^{-19} \text{ C} \).
   - Electron mass, \( m = 9.11 \times 10^{-31} \text{ kg} \).

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

   - Electron charge, \( e = -1.6 \times 10^{-19} \text{ C} \).
   - Alpha particle mass, \( m_0 = 6.7 \times 10^{-27} \text{ kg} \).
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.

The separation of atoms in a metal is \( \sim 10^{-10} \text{ m} \), so the diffracting electrons must be accelerated to a speed which will give them a de Broglie wavelength of \( \sim 10^{-10} \text{ m} \).
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 $2.0 \times 10^{-26}$ kg travelling in space with a de Broglie wavelength of $6.8 \times 10^{-26}$ m.

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 $2.6 \times 10^{-10}$ 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 $2.6 \times 10^{-10}$ m. The mass of a neutron is $1.7 \times 10^{-27}$ kg.
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.

![Diagram of electron gun with rings on fluorescent screen]

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.

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