AS Level Physics

Chapter 5 – Waves and Particle Nature of Light

5.8.1 Wave-Particle Duality

Notes

Wave-Particle Duality Of Light

Wave Like Nature of Light

Diffraction and interference patterns are formed when light diffracts (spreads out) when it passes through a slit, or when two light waves interfere, resulting in alternating light and dark bands. Light can also be refracted and reflected, and these phenomena can only be explained by thinking of light to have a wave like nature. The ability to polarise light shows that the wave is transverse.

Particle Like Nature of Light

However, to understand the photoelectric effect, you must think of light and all other electromagnetic radiation to have a particle like nature.

For example, a photon (particle) of light is a discrete packet of energy that can interact in a one-to-one way with an electron. All the energy in the photon is given to one electron. (For more detail please read pack 11.2 The Photoelectric effect).

So is light made up of waves or particles?

Light cannot be classified as a wave or a particle. Light can act as waves or particles depending on the situation.

The wave and particle concepts are different models that we can use to help explain how electromagnetic radiation behaves in different situations.

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

De Broglie and the Wave-Particle Duality Theory

Louis de Broglie proposed that, "If 'wave-like' light showed particle properties (photons), 'particles' like electrons should be expected to show wave-like properties".

He proposed that any particle of matter with momentum (p) has a wavelength (λ) that is equal to:

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

Where:

λ = wavelength (known as de Broglie wavelength) measured in m,

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

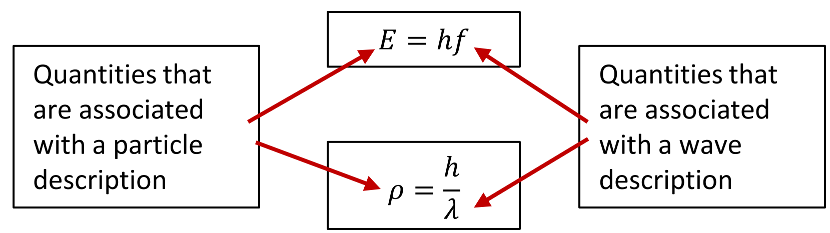
ρ = momentum measured in $kgms^{-1}$,

m = particle mass measured in kg,

v = particle velocity measured in ms^{-1}.

The de Broglie equation implies that the greater a particle's momentum, the shorter its wavelength.

De Broglie equation is a mathematical formula that connects a wave property $(wavelength, \lambda)$ to a particle property $(momentum, \rho)$. Another equation that can be used to connect wave and particle behaviour is $E = hf$. It links $frequency\ (f)$ and $photon\ energy\ (E)$.



The Planck's constant, h, connects the wave quantity to the particle quantity in each of these equations.

Electron Diffraction

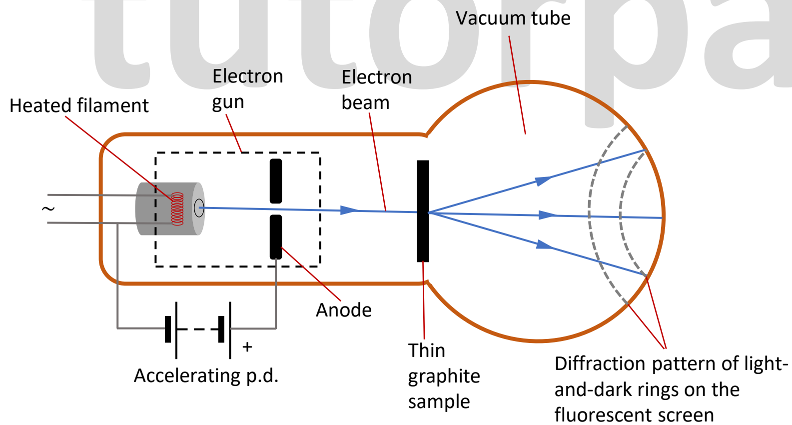
Davisson and Germer demonstrated that electrons were diffracted after travelling through single nickel crystals in the 19th century. In the same year George Thomson directed a high-energy electron beam at a thin metal foil in a vacuum tube, and produced a similar effect. These two pioneering studies provided the proof needed to confirm de Broglie's hypothesis that electrons may display wave-like behaviour.

So, the diffraction of electrons is therefore possible. This tells us that electrons behave like waves when they pass through a fine grid.

Electron diffraction is shown using the apparatus below.

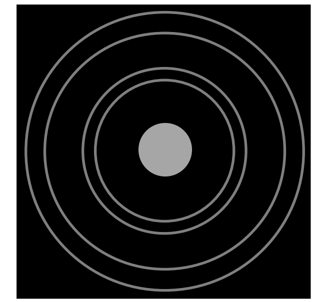
A heated filament cathode produces a beam of fast-moving electrons, which are accelerated to high velocities by the large positive p.d. between the anode and cathode.

Then the electron beam passes through a thin layer of polycrystalline graphite (carbon) producing a diffraction pattern.



Electron Diffraction

On a screen, a diffraction pattern of fuzzy light-and-dark rings is created. The electrons' de Broglie wavelength is on the same order of magnitude as the distance between carbon atoms, therefore this acts as a diffraction grating for electrons. So when an electron beam is aimed at a thin graphite sample, the electron beam passes through the space between the carbon atoms and diffracts in the same way as light does through a diffraction grating.



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

The image displayed on the fluorescent screen is the result of individual light flashes produced as each electron strikes the screen. Therefore the electrons are behaving like particles in this case.

According to wave theory, as the wavelength of the wave increases, so does the spread of the fringes (i.e. fringe spacing) in the diffraction pattern.

In this case, smaller accelerating voltages, i.e. slower electrons, produce widely separated rings in electron diffraction experiments.

When the electron speed is increased, the diffraction pattern rings squash together at the centre. This is consistent with de Broglie's equation:

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

The wavelength is shorter and the spread of lines is narrower when the velocity is higher.

If particles of a higher mass (e.g. neutrons) travelled at the same speed as electrons, the diffraction pattern would be more tightly packed. Since a neutron's mass (and thus momentum) is substantially more than an electron's, the de Broglie wavelength of a neutron is shorter.

Not All Particles Show Wave-Like Properties

Diffraction occurs only when a particle interacts with an object that is roughly the same size as its de Broglie wavelength.

For example, the de Broglie wavelength for a ball with mass 0.058 kg and speed 100 ms^{-1} is $10^{-34}\ m$. That's 10^{19} times smaller than an atom's nucleus. There's nothing that small for it to interact with.

Worked Example:

An electron gun fires an electron of mass 9.11×10^{-31} kg at a speed of $7.5 \times 10^{6}\ ms^{-1}$. What size object will the electron need to interact with in order to diffract?

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{(9.11 \times 10^{-31})(7.5 \times 10^{6})} = 9.7 \times 10^{-11}\ m$$

Therefore, the diffraction of this electron is most likely to occur in crystals with atom layer separation of roughly $9.7 \times 10^{-11}\ m$.

Electron Microscope

Diffraction effects are reduced when the wavelength is shorter. The electron microscope makes use of this fact.

Diffraction blurs detail, and hence diffraction does not produce a clear image. Therefore a shorter wavelength is required to see fine detail in a picture.

Since light distorts detail more than 'electron-waves,' an electron microscope can resolve finer details than a light microscope. They can allow us to examine objects as small as a single strand of DNA.

Please see **'5.8.2 Wave-Particle Duality worked examples'** pack for exam style questions.

For more revision notes, tutorials and worked examples please visit **www.tutorpacks.co.uk.**