

Exercise walk-through

22.3

Wave-particle duality

A-Level Physics

Light is both – and so is matter

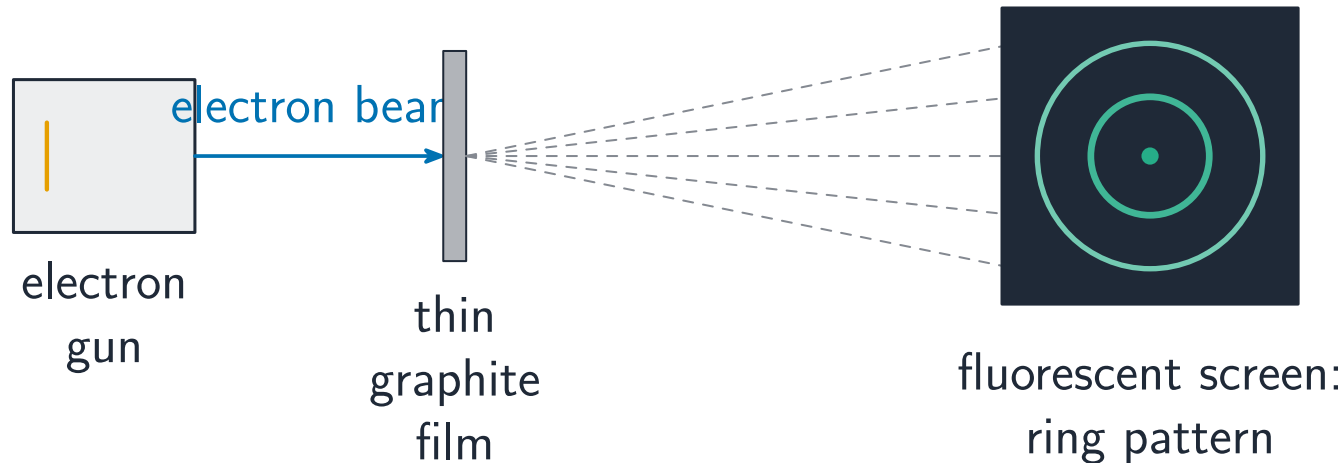
Photoelectric effect $\Rightarrow$ particle. Interference and diffraction $\Rightarrow$ wave. That is **wave-particle duality**. de Broglie: any moving particle has a wavelength

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

Electrons fired at graphite make a ring **diffraction** pattern – only waves diffract, yet electrons do. Faster electron $\Rightarrow$ larger $p \Rightarrow$ shorter $\lambda \Rightarrow$ rings closer together.

Electrons diffract, so electrons are waves

Fire electrons at a thin **crystal lattice** of graphite and they produce **diffraction rings** – a wave effect, from particles with mass. That is **wave-particle duality** : the lattice acts as a natural **diffraction grating** .



Worked example – de Broglie wavelength

Electron accelerated through 2500 V. Find λ .

$E_K = eV$, so $p = \sqrt{2m_e eV}$ and $\lambda = h/p$:

$$\lambda = \frac{h}{\sqrt{2m_e eV}} \approx 2.5 \times 10^{-11} \text{ m}$$

Close to atomic spacings – which is why the electrons diffract off graphite.

Exercises 2.1-2.3

2.1 State **one** phenomenon that is evidence for the **particle** nature of light. [1]

2.2 State **one** phenomenon that is evidence for the **wave** nature of light. [1]

2.3 Write the **de Broglie** equation. [1]

Exercises 2.1·2.3

2.1 State **one** phenomenon that is evidence for the **particle** nature of light. [1]

2.1

- the **photoelectric effect**
-

2.2 State **one** phenomenon that is evidence for the **wave** nature of light. [1]

2.2

- **interference** (e.g. double-slit) or **diffraction**
-

2.3 Write the **de Broglie** equation. [1]

2.3

- $\lambda = h/p$

Exercises 2.4.3.1

2.4 State what **electron diffraction** demonstrates.

[1]

3.1 The de Broglie wavelength of a particle is:

[1]

☐

A hf

B h/p

C E/c

D hc

Exercises 2.4·3.1

2.4 State what **electron diffraction** demonstrates.

[1]

2.4

- that **particles** (electrons) have a **wave nature**

3.1 The de Broglie wavelength of a particle is:

[1]

☐

A hf

B h/p

C E/c

D hc

3.1 B

- de Broglie: $\lambda = h/p$

Exercises 3.2-3.3

3.2 An electron has a momentum of $4.5 \times 10^{-23} \text{ kg m s}^{-1}$. Calculate its de Broglie wavelength. [2]

3.3 Describe the **evidence** that electron diffraction provides for the **wave nature** of particles. [3]

Exercises 3.2-3.3

3.2 An electron has a momentum of $4.5 \times 10^{-23} \text{ kg m s}^{-1}$. Calculate its de Broglie wavelength. [2]

3.2

- $\lambda = h/p$

$$\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34} \text{ J s}}{4.5 \times 10^{-23} \text{ kg m s}^{-1}} = \mathbf{1.5 \times 10^{-11} \text{ m}}$$

3.3 Describe the **evidence** that electron diffraction provides for the **wave nature** of particles. [3]

3.3

- electrons fired at a crystal produce a pattern of **rings/maxima** on a screen
- this is a **diffraction** pattern, and **only waves diffract**
- so the electrons must have a **wave nature** (matching $\lambda = h/p$)

Exercises 3.4·3.5

3.4 Explain what is meant by **wave–particle duality**.

[2]

3.5 Calculate the de Broglie wavelength of an electron moving at $4.9 \times 10^7 \frac{\text{m}}{\text{s}}$. ($m_e = 9.1 \times 10^{-31} \text{ kg}$.)

[3]

Exercises 3.4-3.5

3.4 Explain what is meant by **wave-particle duality**.

[2]

3.4

- matter and radiation show **both** wave-like behaviour (interference/diffraction)
 - **and** particle-like behaviour (photons/photoelectric effect)
-

3.5 Calculate the de Broglie wavelength of an electron moving at $4.9 \times 10^7 \frac{\text{m}}{\text{s}}$. ($m_e = 9.1 \times 10^{-31} \text{ kg}$.)

[3]

3.5

- $p = mv$

$$p = mv = (9.1 \times 10^{-31} \text{ kg})(4.9 \times 10^7 \frac{\text{m}}{\text{s}}) = 4.5 \times 10^{-23} \text{ kg m s}^{-1}$$

- $\lambda = h/p$

$$\lambda = \frac{h}{p} = \frac{6.63 \times 10^{-34} \text{ J s}}{4.5 \times 10^{-23} \text{ kg m s}^{-1}} = \mathbf{1.5 \times 10^{-11} \text{ m}}$$

Exercise 3.6 (a)

3.6 In an electron diffraction tube, electrons are accelerated through a potential difference of 4.8 kV and strike a thin graphite film. Take $h = 6.63 \times 10^{-34}$ J s, $e = 1.60 \times 10^{-19}$ C and the electron mass as 9.11×10^{-31} kg.

(a) **State** what is meant by the **de Broglie wavelength** of a particle.

[2]

Exercise 3.6 (a)

3.6 In an electron diffraction tube, electrons are accelerated through a potential difference of 4.8 kV and strike a thin graphite film. Take $h = 6.63 \times 10^{-34}$ J s, $e = 1.60 \times 10^{-19}$ C and the electron mass as 9.11×10^{-31} kg.

(a) **State** what is meant by the **de Broglie wavelength** of a particle. [2]

(a) the wavelength associated with a **moving particle**

- $\lambda = h/p$, where p is its momentum

Exercise 3.6 (b)

3.6 In an electron diffraction tube, electrons are accelerated through a potential difference of 4.8 kV and strike a thin graphite film. Take $h = 6.63 \times 10^{-34}$ J s, $e = 1.60 \times 10^{-19}$ C and the electron mass as 9.11×10^{-31} kg.

(b) **Determine** the speed of an electron after acceleration.

[3]

Exercise 3.6 (b)

3.6 In an electron diffraction tube, electrons are accelerated through a potential difference of 4.8 kV and strike a thin graphite film. Take $h = 6.63 \times 10^{-34}$ J s, $e = 1.60 \times 10^{-19}$ C and the electron mass as 9.11×10^{-31} kg.

(b) **Determine** the speed of an electron after acceleration. [3]

(b) the work done by the accelerating p.d. becomes kinetic energy: $eV = \frac{1}{2}mv^2$

$$v = \sqrt{\frac{2eV}{m}} = \sqrt{\frac{2 \times (1.60 \times 10^{-19} \text{ C})(4800 \text{ V})}{9.11 \times 10^{-31} \text{ kg}}} = 4.1 \times 10^7 \frac{\text{m}}{\text{s}}$$

Exercise 3.6 (c)

3.6 In an electron diffraction tube, electrons are accelerated through a potential difference of 4.8 kV and strike a thin graphite film. Take $h = 6.63 \times 10^{-34} \text{ J s}$, $e = 1.60 \times 10^{-19} \text{ C}$ and the electron mass as $9.11 \times 10^{-31} \text{ kg}$.

(c) **Determine** its de Broglie wavelength.

[2]

Exercise 3.6 (c)

3.6 In an electron diffraction tube, electrons are accelerated through a potential difference of 4.8 kV and strike a thin graphite film. Take $h = 6.63 \times 10^{-34} \text{ J s}$, $e = 1.60 \times 10^{-19} \text{ C}$ and the electron mass as $9.11 \times 10^{-31} \text{ kg}$.

(c) **Determine** its de Broglie wavelength.

[2]

(c) $\lambda = h/(mv)$

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34} \text{ J s}}{(9.11 \times 10^{-31} \text{ kg})(4.11 \times 10^7 \frac{\text{m}}{\text{s}})} = \mathbf{1.8 \times 10^{-11} \text{ m}}$$

Exercise 3.6 (d)

3.6 In an electron diffraction tube, electrons are accelerated through a potential difference of 4.8 kV and strike a thin graphite film. Take $h = 6.63 \times 10^{-34}$ J s, $e = 1.60 \times 10^{-19}$ C and the electron mass as 9.11×10^{-31} kg.

(d) **Explain** why a diffraction pattern is seen on the screen, and what it demonstrates about electrons. [3]

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3.6 In an electron diffraction tube, electrons are accelerated through a potential difference of 4.8 kV and strike a thin graphite film. Take $h = 6.63 \times 10^{-34} \text{ J s}$, $e = 1.60 \times 10^{-19} \text{ C}$ and the electron mass as $9.11 \times 10^{-31} \text{ kg}$.

(d) **Explain** why a diffraction pattern is seen on the screen, and what it demonstrates about electrons. [3]

(d) the spacing between the graphite atoms is of the same order as this wavelength

- so the electrons are **diffracted** by the atomic planes and the diffracted waves **interfere** to give rings
- diffraction and interference are wave behaviours, so this shows that particles have a **wave nature**

Exercise 3.6 (e)

3.6 In an electron diffraction tube, electrons are accelerated through a potential difference of 4.8 kV and strike a thin graphite film. Take $h = 6.63 \times 10^{-34}$ J s, $e = 1.60 \times 10^{-19}$ C and the electron mass as 9.11×10^{-31} kg.

(e) The accelerating p.d. is **increased**. **State and explain** what happens to the spacing of the rings in the pattern. [2]

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3.6 In an electron diffraction tube, electrons are accelerated through a potential difference of 4.8 kV and strike a thin graphite film. Take $h = 6.63 \times 10^{-34}$ J s, $e = 1.60 \times 10^{-19}$ C and the electron mass as 9.11×10^{-31} kg.

(e) The accelerating p.d. is **increased**. **State and explain** what happens to the spacing of the rings in the pattern. [2]

(e) a larger p.d. gives the electrons more momentum, so $\lambda = h/p$ is **smaller**

- less diffraction means the rings move **closer together**