Past-paper walk-through

Wave-particle duality ▪ 22.3

eXercise

Questions in this set

- 9702/41 J25 Q8 ▪ 13 marks
- 9702/44 J25 Q9 ▪ 8 marks
- 9702/42 N24 Q9 ▪ 9 marks

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 8

9702/41 J25 ▪ Q8 ▪ 13 marks

(a) State what is meant by the de Broglie wavelength. **[1]**

(b) Calculate the de Broglie wavelength of an electron moving at a speed of 4.9×10^7 m s^{-1}. **[2]**

(c) State **one** similarity and **one** difference between an electron and a positron. **[2]**

(d)(i) State the name of this type of reaction. **[1]**

(d)(ii) State what happens to the electron and to the positron. **[2]**

(d)(iii) Explain why two gamma-ray photons are produced, rather than just one. **[1]**

(d)(iv) Show that the kinetic energy of the electron before the collision is 1.1×10^{-15} J. **[1]**

(d)(v) Use the information in **(d)(iv)** to determine, to three significant figures, the wavelength associated with the gamma radiation emitted in the collision. **[3]**

Solution 8

(a)

Mark scheme

- wavelength associated with a moving particle **B1**

Solution 8

(b) Worked steps

The de Broglie relation links a particle's wavelength to its **momentum**, so work out the momentum first.

- $\lambda = \dfrac{h}{p}$, and for a particle $p = mv$, so $\lambda = \dfrac{h}{mv}$.
- $\lambda = \dfrac{6.63 \times 10^{-34}}{9.11 \times 10^{-31} \times 4.9 \times 10^{7}}$
- $\lambda = 1.5 \times 10^{-11}$ m

Solution 8

Use the **electron's** mass, and note the scale of the answer: about a hundredth of a nanometre, comparable with atomic spacings — which is why electrons diffract from crystals and why this wavelength matters at all.

Mark scheme

- $\lambda = h \,/\, p$ **C1**
- $= (6.63 \times 10–34) \,/\, (9.11 \times 10–31 \times 4.9 \times 107)$
- $= 1.5 \times 10–11$ m **A1**

Solution 8

(c) Mark scheme

- similarity: any one point from:
  - same mass
  - same magnitude of charge
  - both leptons **B1**
- difference: any one point from:
  - electron has negative charge, positron has positive charge
  - positron is anti-particle of electron
  - electron is a particle, positron is an anti-particle **B1**

Solution 8

(d)(i)

Mark scheme

- (pair) annihilation **B1**

(d)(ii)

Mark scheme

- their mass gets converted into energy **B1**
- (their mass–energy) becomes the energy of the gamma photons **B1**

Solution 8

(d)(iii)

Mark scheme

- they travel in opposite directions to conserve momentum **B1**

Solution 8

(d)(iv) Worked steps

A *show that* asks for the substitution written out, not just the number.

- $E_K = \frac{1}{2}mv^2$
- $E_K = \frac{1}{2} \times 9.11 \times 10^{-31} \times (4.9 \times 10^7)^2$
- $E_K = 1.1 \times 10^{-15}$ J

Solution 8

Square the **speed** only, and square it before multiplying — $(4.9 \times 10^7)^2$ is 2.4×10^{15}, not 4.9×10^{14}. Writing the substituted line is what earns the mark, because the answer was printed in the question.

Mark scheme

- kinetic energy = ½ × 9.11 × 10–31 × (4.9 × 107)2 = 1.1 × 10–15 J A1

Solution 8

(d)(v) Worked steps

The photon carries away the electron's **whole** energy: the kinetic energy from (d)(iv) plus the energy equivalent of its rest mass.

- Rest energy: $E = mc^2 = 9.11 \times 10^{-31} \times (3.00 \times 10^8)^2 = 8.20 \times 10^{-14}$ J.
- Total: $(1.1 \times 10^{-15}) + (8.20 \times 10^{-14}) = 8.31 \times 10^{-14}$ J.
- A photon's energy is $E = hf$ with $c = f\lambda$, so $E = \dfrac{hc}{\lambda}$ and $\lambda = \dfrac{hc}{E}$.
- $\lambda = \dfrac{6.63 \times 10^{-34} \times 3.00 \times 10^8}{8.31 \times 10^{-14}} = 2.39 \times 10^{-12}$ m

Solution 8

Three marks for three ideas: $E = mc^2$ for the rest energy, $E = hc/\lambda$ for the photon, and the **addition** of the two energies. Leaving the kinetic energy out changes the answer by only about 1%, but it loses a mark — and the question says *to three significant figures* precisely so that the omission shows.

Mark scheme

- E = mc2 **C1**
- E = hc / λ or
- E = hf and c = fλ **C1**
- (1.1 × 10–15) + (9.11 × 10–31 × (3.00 × 108)2) = (6.63 × 10–34 × 3.00 × 108) / λ
- λ = 2.39 × 10–12 m **A1**

Question 9

9702/44 J25 ▪ Q9 ▪ 8 marks

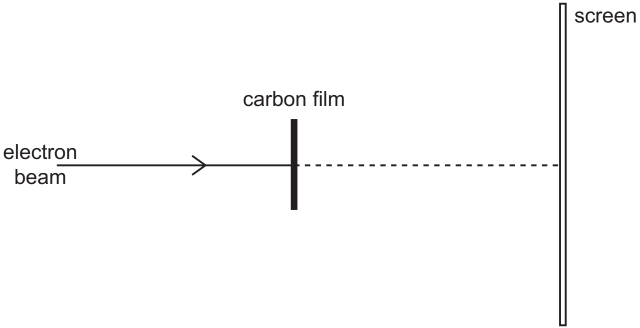
9 **(a)** **(i)** Describe what is meant by wave–particle duality.

Question 9

(ii) State the relationship between the de Broglie wavelength λ of a particle and its momentum p. State the meaning of any other symbols that you use.

Question 9

(b) A narrow beam of electrons, all with the same speed, is incident normally on a carbon film. The electrons then move on to a fluorescent screen, as illustrated in Fig. 9.1.



Question 9

Fig. 9.1

The apparatus is in a vacuum.
The pattern produced on the screen is shown in Fig. 9.2.

Question 9

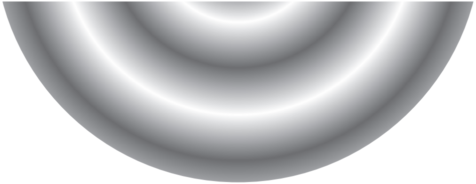


Fig. 9.2 (not to scale)

(i) Explain why the pattern in Fig. 9.2 provides experimental evidence to indicate a wave nature for the electrons.

Question 9

(ii) The speed of the electrons is increased.

Suggest, with a reason, how this change affects the pattern observed on the screen.

Question 9

[Total: 8]

Solution 9

(a)(i)

Mark scheme

- electromagnetic wave can behave like a particle
- moving particle can behave like a wave

(a)(ii)

Mark scheme

- $\lambda = h / p$
- h is the Planck constant

Solution 9

(b)(i) Mark scheme

- Any two points from:
- ▪
- pattern similar to diffraction of light
- ▪
- diffraction (pattern) is characteristic of wave behaviour
- ▪
- rings show constructive and destructive interference

Solution 9

(b)(ii) Worked steps

Two steps, and both are needed for the two marks.

- Faster electrons have **more momentum**, and $\lambda = \dfrac{h}{p}$, so the **de Broglie wavelength decreases**.
- Diffraction angle rises with wavelength ($\sin\theta \propto \lambda$ for a given spacing), so a shorter wavelength diffracts less: the **rings become closer together**.

Say both. "The rings move in" without the wavelength is the observation, not the reason, and the first mark is for the reason.

Solution 9

This is the whole argument for the electron microscope: a faster electron has a shorter wavelength, and a shorter wavelength resolves finer detail than visible light can.

Mark scheme

- (de Broglie) wavelength decreases
- rings become closer together
- 9702/44
- May/June 2025

Question 9

9702/42 N24 ▪ Q9 ▪ 9 marks

Electrons in a vacuum are accelerated from rest through a potential difference (p.d.) V to form a beam. The electrons each have mass m and charge q.

The beam is incident on a graphite crystal that acts as a diffraction grating. After passing through the crystal, the beam reaches a fluorescent screen. An interference pattern is observed on this screen.

(a) Explain what this observation shows about the nature of electrons. **[1]**

(b) Determine an expression, in terms of m, q and V, for the momentum p of an electron in the beam. **[3]**

(c) The p.d. through which the electrons are accelerated is now increased to a greater value.

Describe and explain the effect of this change on the interference pattern observed. **[2]**

(d)(i) On Fig. 9.1, sketch the variation of p with $\frac{1}{\lambda}$. **[2]**

Question 9

(d)(ii) State the name of the quantity represented by the gradient of the line in Fig. 9.1. **[1]**

Solution 9

(a)

Mark scheme

- diffraction is characteristic of wave behaviour so shows that electrons can behave like waves

Solution 9

(b) Worked steps

Know. The accelerating p.d. does work on each electron, and all of that work becomes kinetic energy because the electrons start from rest in a vacuum.

Energy. $qV = \frac{1}{2}mv^2$, so $v = \sqrt{\dfrac{2qV}{m}}$.

Momentum. $p = mv = m\sqrt{\dfrac{2qV}{m}}$.

Answer. $p = \sqrt{2qVm}$.

Check. Simplify by taking the m inside the root: $m \times \sqrt{\dfrac{1}{m}} = \sqrt{m}$. Leaving the answer as mv does not answer a question that asks for an expression in m, q and V, and the speed v is not one of those three. Mark scheme

Solution 9

- $qV = \frac{1}{2}mv^2$
- $p = mv$
- $p = m \times \sqrt{\frac{2qV}{m}}$
- $= \sqrt{2qVm}$

Solution 9

(c)

Mark scheme

- (electrons have) greater momentum so smaller (de Broglie) wavelength
- fringes become closer together

Solution 9

(d)(i) Worked steps

Know. De Broglie's relation says a particle's wavelength is the Planck constant divided by its momentum: $\lambda = \frac{h}{p}$.

Rearrange for the axes given. $p = h \times \frac{1}{\lambda}$, so plotting p against $\frac{1}{\lambda}$ gives a straight line of gradient h.

Draw. A straight line with a positive gradient, passing through the **origin**.

Solution 9

Check. Both marks are in that sentence: straight with positive gradient, and through the origin. This is precisely why the axes were chosen: a graph of p against λ would be a curve, from which the Planck constant could not be read off.

Mark scheme

- straight line with positive gradient
- line with positive gradient passing through the origin

Solution 9

(d)(ii)

Mark scheme

- Planck constant