AS Level Physics

Chapter 11 – Quantum Physics

11.3.2 Wave-Particle Duality

Worked Examples

Wave-Particle Duality

Exam-Style Question 1

(a) A $5.0\ eV$ photon can cause the photoelectric effect from most metals.

(i) State what is meant by the photoelectric effect.

(ii) State what is meant by an electron volt (eV).

(iii) Calculate the value of $5.0\ eV$ in SI units.

(b) A photon of energy $8.0 \times 10^{-19}\ J$ incident on a clean zinc surface can cause photoelectric emission. The maximum kinetic energy of an electron emitted from the surface is $1.1 \times 10^{-19}\ J$.

(i) 1) Define the term work function of a metal.

2) Calculate the work function for zinc.

(ii) 1) Show that the maximum speed v of an electron emitted from the surface is about $5 \times 10^5\ m\ s^{-1}$.

2) Calculate the de Broglie wavelength of an electron emitted from the surface at the maximum speed.

(c) The spacing between atoms in a thin sheet of graphite is about $2.5 \times 10^{-10}\ m$.

(i) A beam of electrons in a vacuum can travel through a thin sheet of graphite placed perpendicular to the beam to produce a pattern of rings on a fluorescent screen beyond the graphite sheet. Explain why this pattern is produced.

(ii) Explain whether or not the electrons in (b)(ii) would be suitable for use in such an experiment.

Wave-Particle Duality

Exam-Style Question 1

(a)A $\mathbf{5.0}\ eV$ photon can cause the photoelectric effect from most metals.
(i) State what is meant by the photoelectric effect.
Emission of electrons from a metal surface when photons (or UV, EM radiation) are incident on the surface.

(ii) State what is meant by an electron volt (eV).
The energy to accelerate an electron through a p.d. of $1\ V$.

(iii) Calculate the value of $\mathbf{5.0}\ eV$ in SI units.

$$5.0\ eV \times 1.6 \times 10^{-19}\ J = 8.0 \times 10^{-19}\ J$$

(b) (i) 1) Define the term work function of a metal.
The minimum energy required to release an electron from the surface of the metal.

(i) 2) Calculate the work function for zinc.
$E = \phi + KE_{max}$ and rearrange for ϕ

$$\phi = E - KE_{max}$$
$$\phi = (8.0 \times 10^{-19}\ J) - (1.1 \times 10^{-19})$$
$$\phi = 6.9 \times 10^{-19}\ J$$

(ii) 1) Show that the maximum speed v of an electron emitted from the surface is about $5 \times 10^5\ m\ s^{-1}$.
Use $KE = \frac{1}{2}mv^2$ and rearrange for v:

$$v = \sqrt{\frac{KE}{\left(\frac{1}{2}\right)(m)}} = \sqrt{\frac{1.1 \times 10^{-19}\ J}{\left(\frac{1}{2}\right)(9.11 \times 10^{-31}\ kg)}}$$
$$v = 4.9 \times 10^5\ m\ s^{-1}$$

Wave-Particle Duality

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(i) State what is meant by the photoelectric effect.

(ii) State what is meant by an electron volt (eV).

(iii) Calculate the value of $5.0\ eV$ in SI units.

(b) A photon of energy $8.0 \times 10^{-19}\ J$ incident on a clean zinc surface can cause photoelectric emission. The maximum kinetic energy of an electron emitted from the surface is $1.1 \times 10^{-19}\ J$.

(i) 1) Define the term work function of a metal.

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(ii) 1) Show that the maximum speed v of an electron emitted from the surface is about $5 \times 10^{5}\ m\ s^{-1}$.

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(c) The spacing between atoms in a thin sheet of graphite is about $2.5 \times 10^{-10}\ m$.

(i) A beam of electrons in a vacuum can travel through a thin sheet of graphite placed perpendicular to the beam to produce a pattern of rings on a fluorescent screen beyond the graphite sheet. Explain why this pattern is produced.

(ii) Explain whether or not the electrons in (b)(ii) would be suitable for use in such an experiment.

Wave-Particle Duality

Exam-Style Question 1

(ii) 2) Calculate the de Broglie wavelength of an electron emitted from the surface at the maximum speed.

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

$$\lambda = \frac{(6.63 \times 10^{-34}\ Js)}{(9.11 \times 10^{-31}\ kg)(4.9 \times 10^{5}\ m\ s^{-1})}$$

$$\lambda = 1.5 \times 10^{-9}\ m$$

(c) The spacing between atoms in a thin sheet of graphite is about $\mathbf{2.5 \times 10^{-10}\ m}$.

(i) Explain why this pattern is produced.

Electrons behave as waves and therefore they diffract. This diffraction is observable because the ordered pattern of the atoms acts as a grating in which the spacing between the atoms (in a thin sheet of graphite) is similar compared to the wavelength of the electrons. This causes interference and a pattern to appear on the screen.

(ii) Explain whether or not the electrons in (b)(ii) would be suitable for use in such an experiment.

The spacing between the atoms is $2.5 \times 10^{-10}\ m$ and the de Broglie wavelength of an electron is $1.5 \times 10^{-9}\ m$ and so the wavelength of the electron is too large to produce a diffraction pattern.

Wave-Particle Duality

Exam-Style Question 2

In 1927 it was shown by experiment that electrons can produce a diffraction pattern.

(a) (i) Explain the meaning of the term diffraction.

(ii) State the condition necessary for electrons to produce observable diffraction when passing through matter, e.g. a thin sheet of graphite in an evacuated chamber.

(b) Show that the speed of an electron with a de Broglie wavelength of $1.2 \times 10^{-10}\ m$ is $6.0 \times 10^{6}\ m\ s^{-1}$.

(c) The electrons in (b) are accelerated to a speed of $6.0 \times 10^{6}\ m\ s^{-1}$ using an electron gun shown diagrammatically in Fig. 8.1.

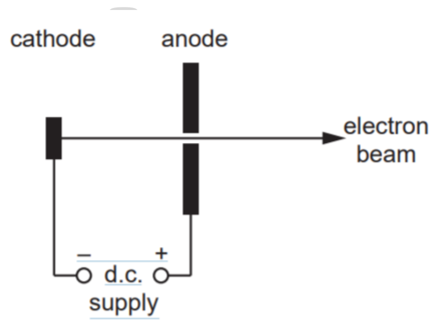

Fig. 8.1

(i) Calculate the potential difference V across the d.c. supply between the cathode and the anode.

(ii) Suggest why, in an electron gun, the cathode is connected to the negative terminal of the supply rather than the positive terminal.

Wave-Particle Duality

Exam-Style Question 2

(a) (i) Explain the meaning of the term diffraction.
Paths spread out after passing through a gap or around an obstacle.

(ii) State the condition necessary for electrons to produce observable diffraction when passing through matter, e.g. a thin sheet of graphite in an evacuated chamber.
Wavelength of electrons must be comparable (similar) to the atomic spacing.

(b) Show that the speed of an electron with a de Broglie wavelength of $1.2 \times 10^{-10}\ m$ is $6.0 \times 10^{6}\ m\ s^{-1}$.
Use $\lambda = \frac{h}{mv}$ and rearrange for v:

$$v = \frac{h}{m\lambda} = \frac{(6.63 \times 10^{-34}\ J\ s)}{(9.11 \times 10^{-31}\ kg)(1.2 \times 10^{-10}\ m\ s^{-1})}$$

$$v = 6.1 \times 10^{5}\ m\ s^{-1}$$

(c) (i) Calculate the potential difference V across the d.c. supply between the cathode and the anode.
Use $eV = \frac{1}{2}mv^2$ and rearrange for V

$$V = \frac{\frac{1}{2}mv^2}{e}$$

$$V = \frac{\left(\frac{1}{2}\right)(9.11 \times 10^{-31}\ kg)(6.0 \times 10^{6}\ m\ s^{-1})^2}{(1.6 \times 10^{-19}\ C)}$$

$$V = 102\ V$$

(c) (ii) Suggest why, in an electron gun, the cathode is connected to the negative terminal of the supply rather than the positive terminal.
Electrons should be repelled by the cathode and attracted by anode. If the cathode was connected to the positive terminal then the electrons will be attracted back to the cathode and the electrons will be slowed down.

Wave-Particle Duality

Exam-Style Question 3

(a) The photoelectric effect suggests that electromagnetic waves can exhibit particle-like behaviour. Explain what is meant by threshold frequency and why the existence of a threshold frequency supports the particle nature of electromagnetic waves.

(b) (i) An alpha particle of mass $6.6 \times 10^{-27}\ kg$ has a kinetic energy of $9.6 \times 10^{-13}\ J$. Show that the speed of the alpha particle is $1.7 \times 10^{7}\ m\ s^{-1}$.

(ii) Calculate the momentum of the alpha particle, stating an appropriate unit.

(iii) Calculate the de Broglie wavelength of the alpha particle.

Wave-Particle Duality

Exam-Style Question 3

(a)The photoelectric effect suggests that electromagnetic waves can exhibit particle-like behaviour. Explain what is meant by threshold frequency and why the existence of a threshold frequency supports the particle nature of electromagnetic waves.

The minimum frequency required for electron emission is known as the threshold frequency. Even if the intensity is increased, there is no electron emission if the frequency is below the threshold frequency, because the photon's energy is less than the work function.

Wave theory cannot explain this as energy of a wave increases with intensity. This tells us that light also has a particle like nature. Light is made up of photons, whose energy depends on its frequency. If the frequency is higher then the threshold frequency, the photon has enough energy to have a one-to-one interaction with an electron. All the energy in the photon is given to one electron.

(b) (i) Show that the speed of the alpha particle is $\mathbf{1.7 \times 10^{7}\ m\ s^{-1}}$.

Use $E_k = \frac{1}{2}mv^2$ and rearrange for v:

$$v = \sqrt{\frac{E_k}{\left(\frac{1}{2}\right)m}} = \sqrt{\frac{9.6 \times 10^{-13}\ J}{\left(\frac{1}{2}\right)(6.6 \times 10^{-27}\ kg)}}$$

$$v = 1.7 \times 10^{7}\ m\ s^{-1}$$

(ii) Calculate the momentum of the alpha particle, stating an appropriate unit.

Use $\rho = mv$

$$\rho = (6.6 \times 10^{-27}\ kg)(1.7 \times 10^{7}\ m\ s^{-1})$$

$$\rho = 1.1 \times 10^{-19}\ kg\ m\ s^{-1}$$

(iii) Calculate the de Broglie wavelength of the alpha particle.

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

$$\lambda = \frac{6.63 \times 10^{-34}\ J\ s}{(6.6 \times 10^{-27}\ kg)(1.7 \times 10^{7}\ m\ s^{-1})}$$

$$\lambda = 5.9 \times 10^{-15}\ m$$

Please see **'11.3.1 Wave-Particle Duality notes'** pack for revision notes.

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