InkPhysics

ANSWER BOOK

Quanta and wave-particle duality

Turning points · Year 13

AQA 3.12.2.4, 3.12.2.5, 3.12.2.6 · CIE 22.1.1, 22.1.2, 22.3.1, 22.3.2, 22.3.3, 22.3.4
OCR A 4.5.1(a), 4.5.1(b), 4.5.2(b), 4.5.2(e), 4.5.3(a), 4.5.3(c)

18 questions · 52 marks

NAVY EDITION

SECTION A · Warm-up

A1 Classical wave theory predicts that a black body's radiated intensity should rise without limit at short wavelengths, towards the ultraviolet (1), in complete contradiction of the measured curve, which peaks and falls (1). [2]

A2 Energy is emitted and absorbed in quanta of size $E = hf$ (1). High-frequency quanta are expensive, so the short-wavelength modes are starved of energy and the curve turns over as observed (1). [2]

A3 Any two of the following, one mark each (2): the existence of a threshold frequency; emission is immediate, with no time to accumulate wave energy; increasing intensity raises the number of electrons but never their maximum kinetic energy. [2]

A4 $p = h/\lambda$ (equivalently $\lambda = h/p$), where h is the Planck constant (1). [1]

A5 One photon interacts with one electron, giving it all of its energy hf (1). Greater intensity means more photons per second, so more electrons per second, but each photon still carries the same energy hf, so the maximum kinetic energy is unchanged (1). [2]

SECTION B · Standard

B1 $\lambda = h/\sqrt{(2meV)}$ (1) [3]
$\lambda = 6.63 \times 10^{-34}/\sqrt{(2 \times 9.11 \times 10^{-31} \times 1.60 \times 10^{-19} \times 150)}$ (1)
$\lambda = 1.0 \times 10^{-10}$ m (1)

B2 $\lambda = h/\sqrt{(2meV)} = 6.63 \times 10^{-34}/\sqrt{(2 \times 9.11 \times 10^{-31} \times 1.60 \times 10^{-19} \times 5000)}$ (1) [2]
$\lambda = 1.7 \times 10^{-11}$ m (1)

B3 $\lambda \propto 1/\sqrt{V}$, so the wavelength falls to a third of its value (1), and the diffraction rings shrink to a third of their radius (1): faster electrons, more momentum, shorter matter waves, tighter pattern (1). [3]

B4 Einstein took light itself to travel as quanta, photons of energy hf (1), one photon releasing one electron (1). Its success showed that electromagnetic radiation, so recently established as a wave, also behaves as particles: wave-particle duality for light (1). [3]

B5 $E = hf$ (1) $= 6.63 \times 10^{-34} \times 1.5 \times 10^{15} = 9.9 \times 10^{-19}$ J (1). [2]

B6 $p = mv = 9.11 \times 10^{-31} \times 4.0 \times 10^{6} = 3.6 \times 10^{-24}$ kg m s^{-1} (1). $\lambda = h/p$ (1) $= 6.63 \times 10^{-34}/(3.6 \times 10^{-24}) = 1.8 \times 10^{-10}$ m (1). [3]

B7 $\lambda = h/\sqrt{(2meV)}$ (1) $= 6.63 \times 10^{-34}/\sqrt{(2 \times 9.11 \times 10^{-31} \times 1.60 \times 10^{-19} \times 48)} = 1.77 \times 10^{-10}$ m, about 1.8×10^{-10} m (1). This wavelength is comparable to the spacing of the atomic planes (1), so the regular planes act as a diffraction grating for the electron waves and a diffraction pattern appears (1). [4]

SECTION C · Stretch

C1 $\lambda = h/\sqrt{(2meV)}$ (1) [4]
rearranges to $V = h^2/(2me\lambda^2)$ (1)
$V = (6.63 \times 10^{-34})^2/(2 \times 9.11 \times 10^{-31} \times 1.60 \times 10^{-19} \times (5.0 \times 10^{-11})^2)$ (1)
$V = 603$ V (1)

C2 An electron gun fires a beam down an evacuated column (1); magnetic coils act as lenses, condensing the beam through a very thin specimen and projecting the transmitted electrons onto a fluorescent screen (1). Denser regions scatter more electrons and appear darker, and the short de Broglie wavelength allows detail far beyond any light microscope (1). [3]

C3 A tip sharpened almost to a single atom is held about a nanometre above a conducting surface (1), close enough for electrons to tunnel across the gap (1). The tunnelling current falls extremely steeply with distance, so scanning the tip across the surface and monitoring the current maps its atoms (1). [3]

C4 The light's 500 nm wavelength is larger than the 90 nm virus, so the optical microscope cannot resolve it (1). Electrons: $\lambda = h/\sqrt{(2meV)} = 6.63 \times 10^{-34}/\sqrt{(2 \times 9.11 \times 10^{-31} \times 1.60 \times 10^{-19} \times 1200)}$ (1) $= 3.5 \times 10^{-11}$ m, about 0.035 nm (1). This is far smaller than 90 nm, so the electron microscope resolves the virus easily (1). [4]

C5 $p = mv = 60 \times 10 = 600$ kg m s^{-1} (1). $\lambda = h/p = 6.63 \times 10^{-34}/600 \approx 1.1 \times 10^{-36}$ m (1). No gap or obstacle is remotely as small as 10^{-36} m, so everyday objects can never show measurable diffraction (1). [3]

C6 Wave theory lets energy arrive continuously and accumulate, so light of any frequency should eventually eject electrons; in fact no electrons are emitted below a threshold frequency (1). Wave theory predicts a delay while a dim source's energy builds up; in fact emission is immediate at any intensity (1). Wave theory predicts brighter light should give each electron more energy; in fact intensity changes the number emitted, never the maximum kinetic energy (1). Photon model: light travels as photons of energy hf, and one photon gives all its energy to one electron (1). Emission happens only if hf exceeds the energy needed to escape the surface, giving the threshold frequency and instant emission (1). Greater intensity means more photons and so more electrons, while the maximum kinetic energy depends only on hf: every observation is accounted for (1). [6]