Page 57 Test yourself on prior knowledge

1 Radio waves (e.g. broadcasting), microwaves (e.g. mobile phone network), infrared (e.g. cooking), visible (e.g. photography), ultraviolet (e.g. fraud detection), x-rays (e.g. medical imaging), gamma rays (e.g. radiotherapy).

2 a)

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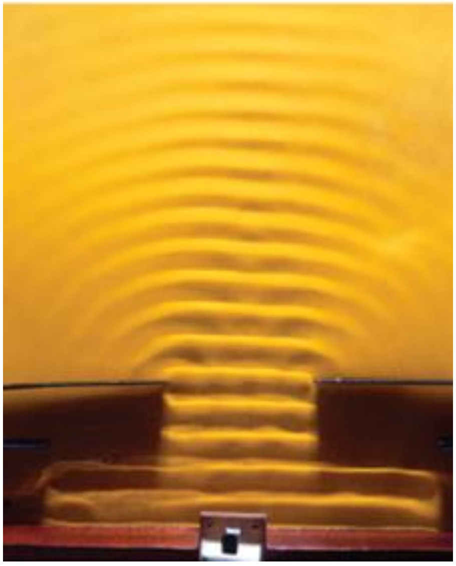

b)

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3 a) The proton has about 2000 times the mass of the electron. Kinetic energy and momentum are both directly proportional to mass, so the kinetic energy and momentum of a proton are about 2000 times larger than those of an electron travelling at the same velocity.

b) If they have the same momentum, the velocity of the proton is about 2000 times smaller than that of the electron as its mass is 2000 times larger. Kinetic energy depends on mass and the square of the velocity, so the kinetic energy of a proton is about 2000 times smaller than that of an electron of the same momentum.

We can show this relationship mathematically:

$$p = mv$$

$$E_k = \tfrac{1}{2}mv^2 = \frac{(mv)^2}{2m}$$

$$E_k = \frac{p^2}{2m}$$

4 The momentum of the atom is in the opposite direction but of the same magnitude.

5 Energy moves from the chemical store (battery) through an electrical current to the thermal store (filament) where it spreads to the surroundings warming them, by radiation (light).

Page 59–60 Test yourself

1 a) When light of a minimum frequency shines on the surface of a metal, photoelectrons are released; more intense light of the same (or higher) frequency releases more photoelectrons; below the minimum frequency, no photoelectrons are released.

b) Wave theory predicts that electrons will be emitted when very bright light is incident on the metal surface, no matter what the frequency.
Wave theory predicts that there will be a delay before electrons are emitted.

2 a) Efficiency $= \frac{\text{useful power out}}{\text{power put in=IV}}$

$= \frac{2.5\text{ mW}}{1.5\text{ V} \times 6.0\text{ mA}}$

$= 0.28$

b) 2.5 mW $= \frac{dn}{dt} \times \frac{hc}{\lambda}$ where $\frac{dn}{dt}$ is the number of photons emitted per second.

$$\frac{dn}{dt} = 2.5\text{mW} \times \frac{\lambda}{hc}$$

$$= 2.5 \times 10^{-3} \times \frac{532 \times 10^{-9}}{6.63 \times 10^{-34} \times 3 \times 10^{8}}$$

$= 6.7 \times 10^{15}$ photons per second

3 The photoelectric effect can be seen using UV, but also with visible light for certain metals – it depends on the material. The alkali metals, calcium and barium have low enough work functions for visible light to remove electrons from the metal surface.

4 a) The photoelectric effect is not observed; the electroscope does not discharge.

b) The photoelectric effect is observed; the electroscope discharges.

5 a) The photoelectric effect was evidence that light does not always behave as a wave. Wave theory predicted that a strong white light would discharge a negatively charged electroscope. Only a particle theory can explain why a very weak source of ultraviolet light can remove electrons from a metal surface.

b) More energy is required to release photoelectrons from zinc than from sodium: zinc has a greater work function than sodium.

c) The photoelectrons will have a greater kinetic energy because ultraviolet photons have more energy than visible-light photons.

6 The gamma photon carries more energy because its frequency is higher.

7 a) There are more photons emitted, each carrying the same amount of energy as before.

b) The same number of photons are emitted, but they each carry more energy.

8 Any two of: electric charge; energy carried by photons; energy of electrons in atoms. Also other quantum numbers: strangeness, charm and hadron number, for example.

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9 The energy needed to escape from the potential well equals the threshold energy.

10 Yellow $E = hf$

$= 6.63 \times 10^{-34}$ J s $\times 5.187 \times 10^{14}$ Hz
$= 3.44 \times 10^{-19}$ J
$= 3.44 \times 10^{-19}$ J $\div 1.6 \times 10^{-19}$ C $= 2.15$ eV

Green $E = hf$

$= 6.63 \times 10^{-34}$ J s $\times 5.490 \times 10^{14}$ Hz
$= 3.64 \times 10^{-19}$ J
$= 3.64 \times 10^{-19}$ J $\div 1.6 \times 10^{-19}$ C $= 2.27$ eV

Blue $E = hf$

$= 6.63 \times 10^{-34}$ J s $\times 6.879 \times 10^{14}$ Hz
$= 4.56 \times 10^{-19}$ J
$= 4.56 \times 10^{-19}$ J $\div 1.6 \times 10^{-19}$ C $= 2.85$ eV

Violet $E = hf$

$= 6.63 \times 10^{-34}$ J s $\times 7.409 \times 10^{14}$ Hz
$= 4.91 \times 10^{-19}$ J
$= 4.91 \times 10^{-19}$ J $\div 1.6 \times 10^{-19}$ C $= 3.07$ eV

Ultraviolet $E = hf$

$= 6.63 \times 10^{-34}$ J s $\times 8.203 \times 10^{14}$ Hz
$= 5.44 \times 10^{-19}$ J
$= 5.44 \times 10^{-19}$ J $\div 1.6 \times 10^{-19}$ C $= 3.40$ eV

11 Sodium $2.29 \times 1.6 \times 10^{-19} = 3.66 \times 10^{-19}$ J

Selenium $5.11 \times 1.6 \times 10^{-19} = 8.18 \times 10^{-19}$ J

12 The photon energy does two things: give the photoelectron kinetic energy, and do work to remove it from the metal. A certain amount of energy from the incident radiation is needed to release the photoelectron; this is the work function of the metal. Only the energy above this amount is converted to kinetic energy of the photoelectron.

Page 62–63 Test yourself

13 a) Sodium: photoelectrons are released with blue, violet and ultraviolet light as the energy of these photons is greater than the threshold energy.

Selenium: no photoelectrons are released as the threshold energy is more than the energy of the photons of any of the given frequencies.

b) Maximum kinetic energy for sodium is:

(blue) $2.85 - 2.29 = 0.56$ eV $= 8.96 \times 10^{-20}$ J

(violet) $3.07 - 2.29 = 0.78$ eV $= 1.25 \times 10^{-19}$ J

(ultraviolet) $3.40 - 2.29 = 1.11$ eV $= 1.78 \times 10^{-19}$ J

14 Iron has the largest work function – the energy of visible light photons is greater than the work function of caesium, but less than that of iron.

UV light has more energy than visible light.

15 a) threshold frequency $= \frac{\text{work function (J)}}{\text{Planck's constant}}$

$$= \frac{4.26 \times 1.6 \times 10^{-19}}{6.63 \times 10^{-34}}$$

$$= 1.03 \times 10^{15}\,\text{Hz}$$

b) Photoelectrons are emitted as the threshold frequency is lower than the UV light's frequency.

c) Energy of the incident photons in eV = *hf/e*

$$\frac{6.63 \times 10^{-34} \times 1.50 \times 10^{15}}{1.6 \times 10^{-19}} = 6.21\,\text{eV}$$

KE of electrons is the difference between incident photon energy and threshold energy

$= 6.21$ eV $- 4.26$ eV $= 1.95$ eV $= 3.12 \times 10^{-19}$ J

16 a) wavelength $(\lambda) = \frac{hc}{E}$

$E = 2.87 \times 1.6 \times 10^{-19} = 4.59 \times 10^{-19}$ J

$$\lambda = \frac{6.63 \times 10^{-34} \times 3 \times 10^{8}}{4.59 \times 10^{-19}} = 433\text{ nm}$$

b) No, electrons are not emitted – the wavelength of light is longer than the threshold wavelength.

c) $\frac{1}{2}mv_{max}^2 = \frac{hc}{\lambda} - \phi$

$= \frac{6.63\times10^{-34}\times3\times10^{8}}{400\times10^{-9}} - 4.592\times10^{-19}$

$= 4.973 \times 10^{-19} - 4.592 \times 10^{-19}$

$= 3.81 \times 10^{-20}$ J = 0.238 eV

Page 64 Activity

Diffraction rings

1 Electrons are diffracted as they pass through the crystal lattice.

2 The spacing and wavelength are similar.

3 **a)** Assuming all energy of the electron is $KE = \frac{1}{2}mv^2$

$KE = eV$

$= 1.6 \times 10^{-19} \times 2000$
$= 3.2 \times 10^{-16}$ J

b) $KE = eV$

$= 1.6 \times 10^{-19} \times 4000$
$= 6.4 \times 10^{-16}$ J

4 When V = 2000 V:

$v = \sqrt{(2E/m)}$

$= \sqrt{(2 \times 3.2 \times 10^{-16} / 9.11 \times 10^{-31})}$

$= 2.65 \times 10^{7}$ m s^{-1}

When V = 4000 V:

$v = \sqrt{(2E/m)}$

$= \sqrt{(2 \times 6.4 \times 10^{-16} / 9.11 \times 10^{-31})}$

$= 3.75 \times 10^{7}$ m s^{-1}

5 When V = 2000 V:

$\lambda = h/mv$

$= 6.63 \times 10^{-34}/9.11 \times 10^{-31} \times 2.65 \times 10^{7}$

$= 2.74 \times 10^{-11}$ m

When V = 4000 V:

$\lambda = h/mv$

$= 6.63 \times 10^{-34}/9.11 \times 10^{-31} \times 3.75 \times 10^{7}$

$= 1.94 \times 10^{-11}$ m.

6 Higher accelerating voltage means higher energy electrons, and these have a shorter wavelength than lower energy electrons. The electron wavelength is already shorter than the atomic separation so making the wavelength of electrons even smaller means less diffraction.

Page 65 Test yourself

17 a) Strong diffraction occurs if the wavelength is the same order of magnitude as the spacing/gap/obstacle.

b) The approximate spacing is 1 nm because X-rays are strongly diffracted and their wavelength is about 1 nm.

18 a) de Broglie wavelength, $\lambda = h/mv$

Since h is constant and v is the same for the two particles, the de Broglie wavelength of the neutron, $\lambda_n = (m_e/m_n)\,\lambda_e$

$= (9.11 \times 10^{-31}/1.67 \times 10^{-27}) = 5.46 \times 10^{-4}\,\lambda_e$

b) The neutron's wavelength is about 1800 times smaller than that of the electron and much smaller than the lattice spacing of crystals so they are not diffracted. (The neutron wavelength is closer in size to the diameter of a nucleus than that of an atom.)

19 a) $\lambda = h/mv = 6.63 \times 10^{-34}$ J s/(70 kg × 5 m s^{-1}) = 1.89×10^{-36} m

b) $\lambda = h/mv = 6.63 \times 10^{-34}$ J s/(1.67×10^{-27} kg × 1×10^{6} m s^{-1}) = 4×10^{-13} m

c) Anything sensible that about the wavelength of the person, e.g. it is too small to measure, so we are not aware of it; all physical objects, even nucleons, are many times larger than this wavelength so we do not experience diffraction.

d) Take the mass of an average pupil as 60 kg, and walking speed as 2ms^{-1}

$\lambda = h/mv$ = 100 J s/60 kg × 2ms^{-1} = 0.83 m

This is similar to the width of the doorway so the pupils would diffract through it.

20 a) Diffraction of neutrons is evidence of wave behaviour; kinetic energy and momentum are (classically) properties of particles with mass so, taken together, these facts are evidence for wave–particle duality.

b) Polarisation is wave behaviour, and X-rays were considered to be waves, so this does not provide of X-rays describes behaviour of waves so this does not evidence for wave–particle duality.

c) Diffraction is wave behaviour, and microwaves are also thought of as electromagnetic waves so this does not evidence for wave–particle duality.

Pages 66–68 Practice questions

1 D

2 A

3 C

4 B

5 C

6 B

7 A

8 D

9 B

10 A

11 a) A photoelectron is an electron released from a metal [1]
when the surface of the metal is irradiated/the electron absorbs energy from a photon [1]

b) An electron can only absorb one photon. Photons of a given wavelength each carry the same amount of energy. Energy from each photon is used to release the photoelectron, and any surplus is the electron's KE. Electrons released from the surface have the most KE as they need to smallest amount of energy to be released. [1]

c) Energy of photon = work function + max KE of photoelectron [1]

$= (4.70 \times 1.6 \times 10^{-19}) + 2.4 \times 10^{-20}$

$= 7.76 \times 10^{-19}$ J [1]

Wavelength = *hc/E* [1]

$= 6.63 \times 10^{-34} \times 3 \times 10^{8} / 7.76 \times 10^{-19}$

$= 2.56 \times 10^{-7}$m [1]

12 a) Electron diffraction [1]

b) Any 5 from:

- The new theory must be able to explain experimental data
- e.g. electron diffraction patterns;
- experimental data must be reproducible
- e.g. by scientists in other laboratories using different crystals;
- evidence and theory must be presented to peers and peer reviewed
- e.g. in the literature and at conferences.

QWC [1]

13 a) Threshold frequency is the minimum frequency required [1]
to release photoelectrons from a material. [1]

b) The energy carried by a photon is proportional to its frequency: $E = hf$ [1]
The energy needed to release photoelectrons is different for different materials. [1]

c) Work function is the minimum energy needed to release an electron from the surface of a metal. It is measured in J or eV. [1]

14 a) Wave–particle duality is the concept that waves may behave in particle-like ways [1]
and wave-like behaviour is exhibited by particles. [1]

b) The de Broglie wavelength $= h/mv$ [1]

$= 6.63 \times 10^{-34} / (3.2 \times 10^{4} \times 9.11 \times 10^{-31})$ [1]

$= 2.3 \times 10^{-8}$ m [1]

c) The proton's mass (and momentum) is greater than the mass and momentum of an electron by factor of 1836 so the proton's wavelength is smaller by the same factor: [1]

$\lambda_p = 2.3 \times 10^{-8}$ m/1836 $= 1.2 \times 10^{-11}$ m [1]

15 a) $E = hf = 6.63 \times 10^{-34}$ J s $\times 1.4 \times 10^{15}$ Hz [1]

$= 9.28 \times 10^{-19}$ J [1]

b) Number of photons per second = total energy per second/energy per photon [1]

$= 3.0 \times 10^{7}/9.28 \times 10^{-19}$

$= 3.23 \times 10^{11}$ [1]

16 Any 5 from:

- electrons released (with range of KE) when light above a threshold frequency shines on a material;
- individual photons of light interact with individual electrons;
- the energy of each photon (which is proportional to frequency) must be greater than the energy needed to release an electron – hence threshold frequency;
- above the threshold, increasing intensity increases number of photoelectrons released;
- increasing intensity increases the number of photons and therefore the number of electrons emitted;
- increasing frequency increases the maximum KE of electrons released;
- as photon has more energy to transfer to electron but amount required to release the electron remains the same.

QWC [1]

17 a) i) The minimum energy needed [1]
to release an electron from the surface of a metal. [1]

ii) Photon energy, $E = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}\times3\times10^{8}}{280\times10^{-9}} = 7.10 \times 10^{-9} J$ [1]

7.1×10^{-19} J $= 7.1 \times 10^{-19}/1.6 \times 10^{-19} = 4.44$ eV [1]

This is greater than the work function (3.6 eV), so electrons will be released. [1]

b) Using Einstein's photoelectric equation $KE_{max} = E - \phi$ and $KE_{max} = eV_{stop}$
(a photon needs to supply an electron with at least enough energy to release it – the work function – and to overcome the 2V potential difference) [1]

$$E = eV_{stop} + \phi = (1.6 \times 10^{-19} \times 2) + (3.6 \times 1.6 \times 10^{-19})$$
$$= 8.96 \times 10^{-19}\text{ J}$$ [1]

This is the minimum energy required, which corresponds to a maximum wavelength of:

$\lambda = \frac{hc}{E} = \frac{6.63\times10^{-34}\times3\times10^{8}}{8.96\times10^{-19}} = 221\ \text{nm}$ [1]

Pages 68–69 Stretch and challenge

18 a) The electrons have an associated wavelength that is similar in size to the lattice spacing.

b) i) Kinetic energy = $eV = 1.6 \times 10^{-19} \times 5000 = 8 \times 10^{-16}$ J

ii) Velocity, $v = \sqrt{\frac{2E}{m}} = \sqrt{\frac{2\times8\times10^{-16}}{9.11\times10^{-31}}} = 4.19 \times 10^{7}\,\text{ms}^{-1}$

iii) de Broglie wavelength, $\lambda = h/mv = 6.63 \times 10^{-34} / (9.11 \times 10^{-31} \times 4.19 \times 10^{7}) = 1.7 \times 10^{-11}$ m

c) i) The electron's KE is halved.

ii) The momentum of the electrons decreases by a factor of $\sqrt{2}$ (v is proportional to $\sqrt{E}$).

iii) The de Broglie wavelength increases by a factor of $\sqrt{2}$ (λ is proportional to $1/mv$).

d) The diameter of the rings increases because the electrons are travelling more slowly, have a longer wavelength and are diffracted more.

e) The electrons are charged particles. When they move through a magnetic field they experience a force that deflects them.

19 a) Each image has fringes, regions of dark and bright patches (the colour and scale cannot be directly compared)

b) These fringe patterns are only seen when waves diffract and interfere. These pictures provide evidence that protons, electrons and single photons exhibit wave-like behaviour.

c) The de Broglie wavelength for protons is about 1800 times smaller than that for electrons (see, for example, Q14), and this in turn is much smaller than the wavelength of visible light. Therefore, the separation (and size) of the slits would need to be different in each case in order for (diffraction and) interference to occur.
They would need to be much (narrower and) closer together for electrons than photons and for protons than electrons.