

Exercise walk-through

# 22.1

## Energy and momentum of a photon

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A-Level Physics

# Electrons sit on discrete rungs

In an isolated atom, electrons occupy **discrete energy levels**. Lowest is the **ground state**; the others are **excited states**. Energies are written negative, with  $E = 0$  just free of the atom. Hydrogen:  $E_1 = -13.6 \text{ eV}$ .

$$hf = E_2 - E_1$$

Down a level: emit (bright line). Up a level: absorb (dark line).

# Line spectra are a fingerprint

Because the levels are fixed, only certain photon energies appear – a **line spectrum**.

## emission

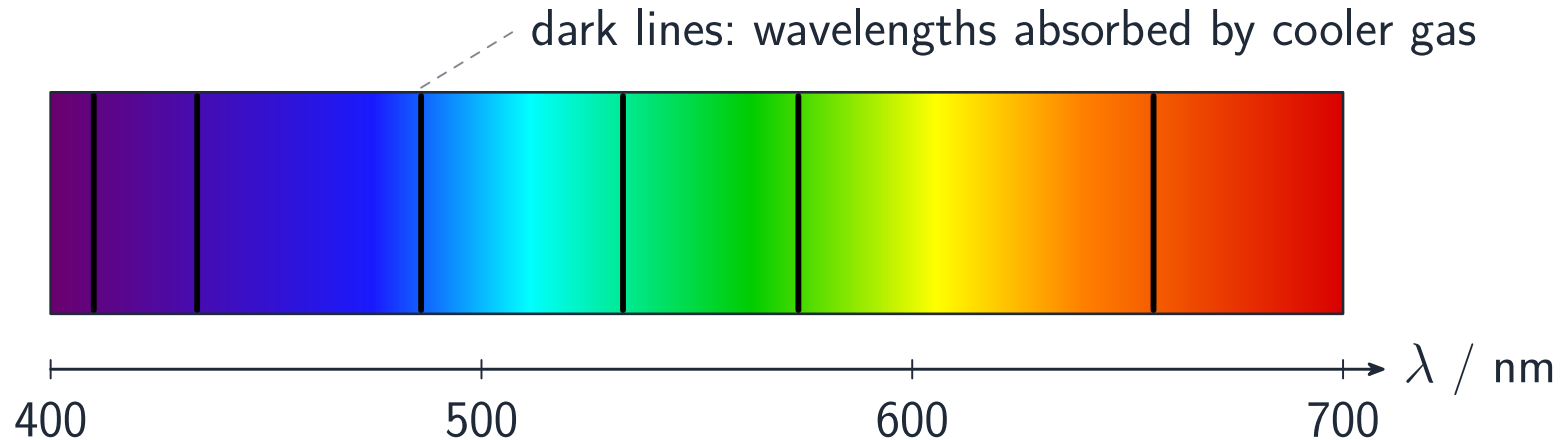
sharp **bright** lines on  
a dark background

## absorption

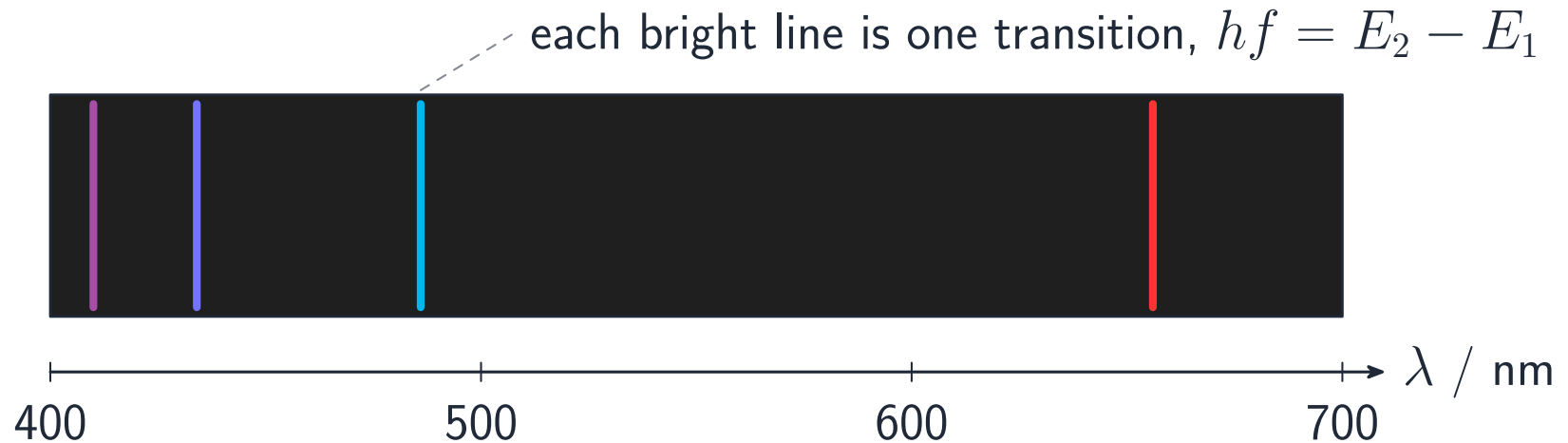
sharp **dark** lines on a  
continuous background

# Emission and absorption are the same fingerprint

Hot gas **emits** at its own frequencies; the same cool gas in front of a continuous source gives an **absorption spectrum** at exactly those frequencies – the dark **Fraunhofer lines** in sunlight name the elements in the Sun.



# Emission spectrum



The emission spectrum of hydrogen is a set of sharp bright lines on a dark background

# Calculations

For a transition between two known levels:

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## Exercises 2.1-2.3

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**2.1** Write the formula for the **energy** of a photon.

[1]

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**2.2** State the value of the **Planck constant**.

[1]

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**2.3** Find the energy of a photon of frequency  $5.0 \times 10^{14}$  Hz.

[2]

## Exercises 2.1-2.3

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2.1 Write the formula for the **energy** of a photon.

[1]

2.1

- $E = hf$  (or  $E = hc/\lambda$ )

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2.2 State the value of the **Planck constant**.

[1]

2.2

- $h = 6.63 \times 10^{-34} \text{ J s}$

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2.3 Find the energy of a photon of frequency  $5.0 \times 10^{14} \text{ Hz}$ .

[2]

2.3

- $E = hf$

$$E = hf = (6.63 \times 10^{-34} \text{ J s})(5.0 \times 10^{14} \text{ Hz}) = \mathbf{3.3 \times 10^{-19} \text{ J}}$$

## Exercises 2.4·3.1

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**2.4** Convert your answer to **electronvolts**.

[1]

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**3.1** The momentum of a photon of energy  $E$  is:

[1]

☐

**A**  $hf$

**B**  $E/c$

**C**  $mc$

**D**  $h/c$

## Exercises 2.4·3.1

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2.4 Convert your answer to **electronvolts**.

[1]

2.4

$$E = \frac{3.3 \times 10^{-19} \text{ J}}{1.6 \times 10^{-19} \text{ J eV}^{-1}} = \mathbf{2.1 \text{ eV}}$$

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3.1 The momentum of a photon of energy  $E$  is:

[1]

☐

A  $hf$

B  $E/c$

C  $mc$

D  $h/c$

3.1 B

- photon momentum  $p = E/c$

## Exercises 3.2-3.3

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**3.2** Calculate the energy of a photon of wavelength 500 nm. [3]

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**3.3** Calculate the **momentum** of this photon. [2]

## Exercises 3.2-3.3

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**3.2** Calculate the energy of a photon of wavelength 500 nm. [3]

**3.2**

- $E = hc/\lambda$

$$E = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34} \text{ J s})(3.0 \times 10^8 \frac{\text{m}}{\text{s}})}{500 \times 10^{-9} \text{ m}} = \mathbf{4.0 \times 10^{-19} \text{ J}}$$

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**3.3** Calculate the **momentum** of this photon. [2]

**3.3**

- $p = E/c$

$$p = \frac{E}{c} = \frac{4.0 \times 10^{-19} \text{ J}}{3.0 \times 10^8 \frac{\text{m}}{\text{s}}} = \mathbf{1.3 \times 10^{-27} \text{ kg m s}^{-1}}$$

## Exercise 3.4

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**3.4** State what a **photon** is.

[1]

## Exercise 3.4

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3.4 State what a **photon** is.

[1]

3.4

- a quantum (packet) of electromagnetic energy

## Exercise 3.5 (a)

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**3.5** A nucleus of uranium-238 decays by emitting an  $\alpha$ -particle and a single gamma photon. Take  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ ,  $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$ ,  $h = 6.63 \times 10^{-34} \text{ J s}$  and  $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$ .

(a) **State** what is meant by a **photon**.

[2]

## Exercise 3.5 (a)

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**3.5** A nucleus of uranium-238 decays by emitting an  $\alpha$ -particle and a single gamma photon. Take  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ ,  $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$ ,  $h = 6.63 \times 10^{-34} \text{ J s}$  and  $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$ .

(a) **State** what is meant by a **photon**.

[2]

(a) a photon is a **quantum (discrete packet)** of electromagnetic radiation

- carrying energy  $E = hf$

## Exercise 3.5 (b)

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**3.5** A nucleus of uranium-238 decays by emitting an  $\alpha$ -particle and a single gamma photon. Take  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ ,  $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$ ,  $h = 6.63 \times 10^{-34} \text{ J s}$  and  $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$ .

(b) The gamma photon carries an energy of 0.050 MeV. **Determine** its wavelength. [3]

## Exercise 3.5 (b)

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**3.5** A nucleus of uranium-238 decays by emitting an  $\alpha$ -particle and a single gamma photon. Take  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ ,  $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$ ,  $h = 6.63 \times 10^{-34} \text{ J s}$  and  $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$ .

(b) The gamma photon carries an energy of 0.050 MeV. **Determine** its wavelength. [3]

(b)  $E = 0.050 \times 1.60 \times 10^{-13} \text{ J} = 8.0 \times 10^{-15} \text{ J}$

$$\lambda = \frac{hc}{E} = \frac{(6.63 \times 10^{-34} \text{ J s})(3.00 \times 10^8 \frac{\text{m}}{\text{s}})}{8.0 \times 10^{-15} \text{ J}} = \mathbf{2.5 \times 10^{-11} \text{ m}}$$

## Exercise 3.5 (c)

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**3.5** A nucleus of uranium-238 decays by emitting an  $\alpha$ -particle and a single gamma photon. Take  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ ,  $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$ ,  $h = 6.63 \times 10^{-34} \text{ J s}$  and  $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$ .

(c) **Determine** the momentum of that photon.

[2]

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**3.5** A nucleus of uranium-238 decays by emitting an  $\alpha$ -particle and a single gamma photon. Take  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ ,  $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$ ,  $h = 6.63 \times 10^{-34} \text{ J s}$  and  $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$ .

(c) **Determine** the momentum of that photon.

[2]

(c)  $p = E/c$

$$p = \frac{E}{c} = \frac{8.0 \times 10^{-15} \text{ J}}{3.00 \times 10^8 \frac{\text{m}}{\text{s}}} = \mathbf{2.7 \times 10^{-23} \text{ N s}}$$

## Exercise 3.5 (d)

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**3.5** A nucleus of uranium-238 decays by emitting an  $\alpha$ -particle and a single gamma photon. Take  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ ,  $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$ ,  $h = 6.63 \times 10^{-34} \text{ J s}$  and  $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$ .

(d) The photon is emitted by a nucleus that was at rest. **Explain** why the nucleus recoils, and **determine** its recoil speed, given that its mass is 234 u. [3]

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(d) The photon is emitted by a nucleus that was at rest. **Explain** why the nucleus recoils, and **determine** its recoil speed, given that its mass is 234 u. [3]

(d) momentum is conserved and the nucleus started at rest, so it must recoil with momentum **equal and opposite** to the photon's

$$v = \frac{p}{m} = \frac{2.67 \times 10^{-23} \text{ kg m s}^{-1}}{(234)(1.66 \times 10^{-27} \text{ kg})} = \mathbf{6.9 \times 10^{-2} \frac{\text{m}}{\text{s}}}$$

## Exercise 3.5 (e)

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**3.5** A nucleus of uranium-238 decays by emitting an  $\alpha$ -particle and a single gamma photon. Take  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ ,  $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$ ,  $h = 6.63 \times 10^{-34} \text{ J s}$  and  $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$ .

(e) Gamma radiation from a sample of this nuclide has a **single** wavelength. **Suggest** what this tells you about the energy levels of the nucleus. [2]

## Exercise 3.5 (e)

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**3.5** A nucleus of uranium-238 decays by emitting an  $\alpha$ -particle and a single gamma photon. Take  $1 \text{ u} = 1.66 \times 10^{-27} \text{ kg}$ ,  $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$ ,  $h = 6.63 \times 10^{-34} \text{ J s}$  and  $1 \text{ MeV} = 1.60 \times 10^{-13} \text{ J}$ .

(e) Gamma radiation from a sample of this nuclide has a **single** wavelength. **Suggest** what this tells you about the energy levels of the nucleus. [2]

(e) the nucleus has **discrete energy levels**

- the photon energy is the difference between two definite levels, and a single wavelength means every nucleus in the sample makes the **same** transition