A-LEVEL PHYSICS • EXERCISE SHEET

22.1 Energy and momentum of a photon

Name: _____ Class: _____ Date: _____ **Total: 24 marks**

KEY WORDS photon 光子 • momentum 动量 • electronvolt 电子伏特 • wavelength 波长 • electron 电子

Objective

Build the skills to answer exam questions on the **photon** — its energy and momentum.

You must be able to:

- use $E = hf = \dfrac{hc}{\lambda}$ and the **electronvolt**
- use $p = E/c$ for the photon momentum

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Photons

A **photon** is a **quantum** (packet) of electromagnetic energy:

$$E = hf = \frac{hc}{\lambda}, \qquad p = \frac{E}{c}$$

$$E = hf = \frac{hc}{\lambda}, \qquad p = \frac{E}{c},$$

with $h = 6.63 \times 10^{-34}$ J s. The **electronvolt**: 1 eV $= 1.6 \times 10^{-19}$ J.

Worked example. $\lambda = 500$ nm: $E = \dfrac{hc}{\lambda} = \dfrac{(6.63 \times 10^{-34})(3.0 \times 10^{8})}{500 \times 10^{-9}} = 4.0 \times 10^{-19}$ J.

2 Practice

Now apply the methods above.

2.1 Write the formula for the **energy** of a photon. [1]

2.2 State the value of the **Planck constant**. [1]

2.3 Find the energy of a photon of frequency 5.0×10^{14} Hz. [2]

2.4 Convert your answer to **electronvolts**. [1]

3 Exam-style questions

3.1 The momentum of a photon of energy E is: [1]

- **A** hf
- **B** E/c
- **C** mc
- **D** h/c

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

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

3.4 State what a **photon** is. [1]

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

(a) **State** what is meant by a **photon**. [2]

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

(c) **Determine** the momentum of that photon. [2]

(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]

(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]

Solutions

Each answer shows the steps, then the **result**.

2.1

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

2.2

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

2.3

- $E = hf$

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

2.4

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

3.1 B

- photon momentum $p = E/c$

3.2

- $E = hc/\lambda$

$$E = \frac{(6.63 \times 10^{-34}\text{ J s})(3.0 \times 10^{8}\text{ m s}^{-1})}{500 \times 10^{-9}\text{ m}} = \mathbf{4.0 \times 10^{-19}}\text{ J}$$

3.3

- $p = E/c$

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

3.4

- a **quantum (packet) of electromagnetic energy**

3.5

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

- carrying energy $E = hf$

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

$$\lambda = \frac{hc}{E} = \frac{(6.63 \times 10^{-34}\text{ J s})(3.00 \times 10^{8}\text{ m s}^{-1})}{8.0 \times 10^{-15}\text{ J}} = \mathbf{2.5 \times 10^{-11}}\text{ m}$$

(c) $p = E/c$

$$p = \frac{8.0 \times 10^{-15}\text{ J}}{3.00 \times 10^{8}\text{ m s}^{-1}} = \mathbf{2.7 \times 10^{-23}}\text{ N s}$$

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

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

(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