Past-paper walk-through

Energy and momentum of a photon ▪ 22.1

eXercise

Questions in this set

- 9702/41 N25 Q8 ▪ 11 marks
- 9702/42 M25 Q8 ▪ 10 marks
- 9702/41 N23 Q8 ▪ 10 marks

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 8

9702/41 N25 ▪ Q8 ▪ 11 marks

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

Question 8

nuclide	nuclide mass / u
$^{4}_{2}\alpha$	4.000 407
$^{234}_{90}Th$	233.915 174
$^{238}_{92}U$	

Question 8

9702/41 N25 ▪ Q8 ▪ 11 marks

(b)(i) Calculate the mass, in u, of the uranium-238 nuclide. Give your answer to five decimal places. **[3]**

(b)(ii) Determine a value for the wavelength of the gamma radiation emitted during the decay of the uranium-238 nucleus. **[3]**

(b)(iii) In practice, the rebound kinetic energy of the thorium nucleus is **not** negligible. Explain, without further calculation, how your answer in **(b)(ii)** compares with the true wavelength of gamma radiation emitted during the decay of the uranium-238 nucleus. **[1]**

Question 8

9702/41 N25 ▪ Q8 ▪ 11 marks

(c) Gamma radiation emitted during the decay of a sample of uranium-238 has a single wavelength.
Nuclei of cobalt-60 ($^{60}_{27}$Co) decay by beta emission, and also emit gamma radiation in the process.
Suggest why there is **not** a single wavelength for the gamma radiation emitted during the decay of a sample of cobalt-60. **[2]**

Solution 8

(a)

Mark scheme

- packet / quantum of energy **M1**
- of electromagnetic radiation **A1**

Solution 8

(b)(i) Worked steps

Mass-energy equivalence, worked backwards: the energy released is the mass that vanished.

- $\Delta m = \dfrac{E}{c^2}$, with $E = 4.274$ MeV $= 4.274 \times 10^6 \times 1.60 \times 10^{-19}$ J.
- In atomic mass units: $\Delta m = \dfrac{4.274 \times 10^6 \times 1.60 \times 10^{-19}}{1.66 \times 10^{-27} \times (3.00 \times 10^8)^2} = 0.00458$ u
- The parent's mass is the sum of the products plus that mass defect: $233.915174 + 4.000407 + 0.00458$
- $m = 237.92016$ u (five decimal places, as asked).

Solution 8

Keep every digit until the end: the answer is quoted to five decimal places, so rounding the products early destroys it.

Mark scheme

- $E = c2\Delta m$ **C1**
- $\Delta m = (4.274 \times 106 \times 1.60 \times 10\text{–}19) / (1.66 \times 10\text{–}27 \times (3.00 \times 108)2)$
- $(= 0.00458\ \mathrm{u})$ **C1**
- $m = 233.915174 + 4.000407 + 0.00458$
- $= 237.92016\ \mathrm{u}$ **A1**

Solution 8

(b)(ii) Worked steps

The gamma photon carries the difference between the two quoted energies.

- $E_\gamma = (4.274 - 4.200)$ MeV $= 0.074 \times 10^6 \times 1.60 \times 10^{-19} = 1.18 \times 10^{-14}$ J
- $E = \dfrac{hc}{\lambda}$, so $\lambda = \dfrac{6.63 \times 10^{-34} \times 3.00 \times 10^8}{1.18 \times 10^{-14}}$
- $\lambda = 1.7 \times 10^{-11}$ m

Solution 8

Mark scheme

- $E = hc / \lambda$ or
- $E = hf$ and $c = f\lambda$ **C1**
- $(4.274 – 4.200) \times 1.60 \times 10–13 = (6.63 \times 10–34 \times 3.00 \times 108) / \lambda$ **C1**
- $\lambda = 1.7 \times 10–11$ m **A1**

Solution 8

(b)(iii)

Mark scheme

- (true) energy of gamma photon is smaller so (true) wavelength is larger **B1**

Solution 8

(c)

Mark scheme

- (anti)neutrinos are emitted during beta decay **B1**
- particles emitted during beta decay carry varying amounts of energy, so energy of gamma photon is also variable (between decays) **B1**

Question 8

9702/42 M25 ▪ Q8 ▪ 10 marks

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

Question 8

(b) A laser emits red light of a single wavelength. The light is produced when electrons move from a higher energy level to a lower energy level. The difference in energy between the two levels is 1.96 eV.

(i) Calculate the wavelength of the light.

Question 8

(ii) The power of the beam emitted by the laser is 1.0×10^{-2} W.

Calculate the number of photons emitted per unit time by the laser.

Question 8

(iii) The photons are incident normally on a surface. Half of the number of photons are absorbed by the surface, and half are reflected.

Determine the average force exerted by the beam of photons on the surface.

Question 8

Question 8

[Total: 10]

Solution 8

(a)

Mark scheme

- ▪
- quantum of energy
- ▪
- of electromagnetic radiation

Solution 8

(b)(i) Worked steps

Convert the photon energy from electronvolts to joules first — that conversion is where these questions are usually lost.

- $E = 1.96\ \text{eV} = 1.96 \times 1.60 \times 10^{-19} = 3.14 \times 10^{-19}\ \text{J}$
- $E = \dfrac{hc}{\lambda}$, so $\lambda = \dfrac{hc}{E} = \dfrac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{3.14 \times 10^{-19}}$
- $\lambda = 6.3 \times 10^{-7}\ \text{m}$

Solution 8

That is 630 nm, red light — a sensible check for a 1.96 eV photon.

Mark scheme

- $(\Delta)E = hc\,/\,\lambda$
- $\lambda = (6.63 \times 10–34 \times 3.00 \times 108)\,/\,(1.96 \times 1.60 \times 10–19)$
- $= 6.3 \times 10–7\,\mathrm{m}$

Solution 8

(b)(ii)

Worked steps

Power is energy per second, and each photon carries the energy above.

- $n = \dfrac{P}{E} = \dfrac{1.0 \times 10^{-2}}{3.14 \times 10^{-19}}$
- $n = 3.2 \times 10^{16}\ \mathrm{s}^{-1}$

Mark scheme

- number per unit time = power / energy per photon
- = (1.0 × 10–2) / (1.96 × 1.60 × 10–19)
- = 3.2 × 1016 s–1
- 9702/42
- February/March 2025

Solution 8

(b)(iii) Worked steps

Force is the rate of change of momentum, so the question is really: how much momentum does each photon deliver, and how many arrive each second?

- A photon's momentum is $p = \dfrac{E}{c} = \dfrac{1.96 \times 1.60 \times 10^{-19}}{3.00 \times 10^{8}} = 1.05 \times 10^{-27}\ \mathrm{kg\,m\,s^{-1}}$.

Now the step the marks are really for. **An absorbed photon and a reflected photon do not deliver the same momentum.**

- An **absorbed** photon stops, so its momentum change is p.
- A **reflected** photon comes back the other way, so its momentum change is $2p$.
- Half do each, so the mean change per photon is $\dfrac{2p + p}{2} = 1.5p$.

Then multiply by the rate of arrival from (b)(ii):

Solution 8

- $F = 1.05 \times 10^{-27} \times 3.2 \times 10^{16} \times 1.5$
- $F = 5.0 \times 10^{-11}$ N

Using p for every photon gives 3.4×10^{-11} and using $2p$ gives 6.7×10^{-11}; the factor of 1.5 is what the "half and half" in the question is for. **Mark scheme**

- either: force = rate of change of momentum
- or:
- F = Δp / t
- p = E / c
- half the photons have change in momentum p, the other half have change in momentum 2p

Solution 8

- $F = [(1.96 \times 1.60 \times 10–19) / (3.00 \times 108)] \times 3.2 \times 1016 \times [(2 + 1) / 2]$
- $= 5.0 \times 10–11$ N

Question 8

9702/41 N23 ▪ Q8 ▪ 10 marks

(a)(i) Show that the momentum p of a photon of electromagnetic radiation with wavelength λ is given by

$$p = \frac{h}{\lambda}$$

where h is the Planck constant. **[2]**

(a)(ii) Use the expression in (a)(i) to show that a photon in free space that has a momentum of 9.5×10^{-28} N s is a photon of red light. **[1]**

(b)(i) Show that the number of photons incident on the mirror per unit time is 1.4×10^{15} s^{-1}. **[2]**

(b)(ii) Use the information in (b)(i) to determine the pressure exerted by the light beam on the mirror. **[3]**

Question 8

(c) The beam of red light in (b) is now replaced with a beam of blue light of the same intensity.
Suggest and explain whether the pressure exerted on the mirror by the beam of blue light is less than, the same as, or greater than the pressure exerted by the beam of red light. **[2]**

Solution 8

(a)(i) Worked steps

Know. A photon has no mass, so its momentum cannot be mv. For anything travelling at the speed of light, momentum and energy are linked by $p = \dfrac{E}{c}$.

Photon energy. $E = hf$ and $c = f\lambda$, so $E = \dfrac{hc}{\lambda}$.

Substitute. $p = \dfrac{E}{c} = \dfrac{hc}{\lambda c}$.

Solution 8

Answer. The c cancels, leaving $p = \dfrac{h}{\lambda}$.

Check. Both starting statements have to appear: the relation between energy and momentum, and the relation between energy and wavelength. Writing $p = \dfrac{h}{\lambda}$ straight down is quoting the result the question asks you to derive.

Mark scheme

- $p = E/c$
- $E = hc/\lambda$ and completion of algebra leading to $p = h/\lambda$

Solution 8

(a)(ii) Worked steps

Know. Turn the momentum into a wavelength, then compare it with the visible spectrum, which runs from about 400 nm (violet) to about 700 nm (red).

Equation. $\lambda = \frac{h}{p}$.

Substitute. $\lambda = \dfrac{6.63 \times 10^{-34}}{9.5 \times 10^{-28}}$.

Answer. $\lambda = 7.0 \times 10^{-7}$ m $= 700$ nm, which is at the red end of the visible spectrum.

Solution 8

Check. Say the number **and** what it means. A wavelength with no comment does not answer a “show that it is red light” instruction; the mark is for making the comparison.

Mark scheme

- wavelength $= (6.63 \times 10^{-34})/(9.5 \times 10^{-28}) = 700 \times 10^{-9}$ m so red

Solution 8

(b)(i) Worked steps

Know. Two steps. Find the power arriving on the mirror, then divide by the energy each photon carries.
Power. $P = \text{intensity} \times \text{area} = 160 \times (2.5 \times 10^{-6}) = 4.0 \times 10^{-4}$ W.
Energy per photon. From part (a),
$E = pc = (9.5 \times 10^{-28})(3.00 \times 10^{8}) = 2.85 \times 10^{-19}$ J.
Divide. $n = \dfrac{4.0 \times 10^{-4}}{2.85 \times 10^{-19}}$.
Answer. $n = 1.4 \times 10^{15}$ s^{-1}, as required.

Solution 8

Check. The units confirm the method: watts are joules per second, and dividing by joules per photon leaves photons per second. Using the *intensity* without multiplying by the area gives an answer 4×10^5 times too large.

Mark scheme

- power $=$ intensity $\times$ area
- number per unit time $= (160 \times 2.5 \times 10^{-6})/(9.5 \times 10^{-28} \times 3.00 \times 10^{8}) = 1.4 \times 10^{15}$ s^{-1}

Solution 8

(b)(ii) Worked steps

Know. Force is the rate of change of momentum. The mirror **reflects** the light, so each photon arrives with momentum p towards the mirror and leaves with momentum p away from it: its momentum changes by $2p$, not p.

Force. $F = 2p \times n = 2 \times (9.5 \times 10^{-28}) \times (1.4 \times 10^{15}) = 2.7 \times 10^{-12}$ N.

Pressure. pressure $= \dfrac{F}{A} = \dfrac{2.7 \times 10^{-12}}{2.5 \times 10^{-6}}$.

Answer. 1.1×10^{-6} Pa.

Solution 8

Check. The factor of two is the mark this question is really testing. A perfectly black surface would absorb the photons instead, changing each momentum by only p and feeling half the pressure. It is also worth seeing how tiny the answer is: light pressure only matters over huge areas, as in a solar sail.

Mark scheme

- pressure = force / area
- force = rate of change of momentum
- $= 2 \times 9.5 \times 10^{-28} \times 1.4 \times 10^{15}$
- pressure $= (2 \times 9.5 \times 10^{-28} \times 1.4 \times 10^{15})/(2.5 \times 10^{-6}) = 1.1 \times 10^{-6}$ Pa

Solution 8

(c)

Mark scheme

- photons have greater momentum
- **or**
- fewer photons per unit time
- greater photon momentum but smaller number of photons (per unit time) so pressure is the same