Cambridge AS & A Level · Physics 9702 · Notes

Quantum physics A2

Read online at **pastopic.com/cambridge/physics-9702/notes/quantum-physics**

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Read first: **Dynamics**, **Waves**, **Superposition**

What you need to know

By the end of this topic you should be able to:

1. **Understand that electromagnetic radiation has a particle nature**: it can behave as a stream of particles.
2. **Understand that a photon is a quantum of electromagnetic energy**: one indivisible packet.
3. **Recall and use** $E = hf$ for the energy of a photon.
4. **Use the electronvolt (eV) as a unit of energy.**
5. **Understand that a photon has momentum**, given by $p = \dfrac{E}{c}$.
6. **Understand that photoelectrons may be emitted** from a metal surface when electromagnetic radiation falls on it.
7. **Understand and use the threshold frequency and the threshold wavelength.**
8. **Explain photoelectric emission** using the photon energy and the work function energy.
9. **Recall and use** $hf = \Phi + \frac{1}{2}mv_{\max}^2$**.**
10. **Explain why the maximum kinetic energy of the photoelectrons does not depend on the intensity**, while the photoelectric current is proportional to the intensity.
11. **Understand that the photoelectric effect is evidence for a particle nature** of electromagnetic radiation, while interference and diffraction are evidence for a wave nature.
12. **Describe and interpret, in words, how electron diffraction shows** that particles have a wave nature.
13. **Understand the de Broglie wavelength** as the wavelength linked to a moving particle.
14. **Recall and use** $\lambda = \dfrac{h}{p}$**.**
15. **Understand that an isolated atom (for example hydrogen) has discrete electron energy levels.**
16. **Understand what emission and absorption line spectra look like and how they form.**
17. **Recall and use** $hf = E_1 - E_2$**.**

The electromagnetic spectrum and $c = f\lambda$ come from Waves; diffraction and interference from Superposition; momentum and $F = \dfrac{\Delta p}{\Delta t}$ from Dynamics; the energy qV gained by a charge from Electricity.

Understand it

Photons

Light and all other electromagnetic radiation travel as waves: they diffract and interfere. But when the radiation gives its energy to matter, it does so in lumps. Each lump is a **photon**: a **quantum** (a discrete, indivisible packet) **of electromagnetic energy**. A photon's energy depends only on the frequency of the radiation:

$$E = hf = \frac{hc}{\lambda}$$

$h = 6.63 \times 10^{-34}$ J s is the **Planck constant**. Higher frequency (shorter wavelength) means more energy per photon: a gamma-ray photon carries far more energy than a radio photon. A photon of green light, $\lambda = 500$ nm, has $E = \dfrac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{500 \times 10^{-9}} = 3.98 \times 10^{-19}$ J.

A beam of **power** P delivers P joules each second, so the **number of photons per second** is

$$N = \frac{P}{E} = \frac{P}{hf}.$$

One watt of that green light is 2.51×10^{18} photons every second. A brighter beam of the same colour has **more photons**, not bigger ones.

The electronvolt

Photon and electron energies are tiny in joules, so we often use the **electronvolt**: 1 eV is the energy an electron gains when it moves through a potential difference of 1 V.

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

eV → J: multiply by 1.60×10^{-19}. J → eV: divide by it. The green photon has $\dfrac{3.98 \times 10^{-19}}{1.60 \times 10^{-19}} = 2.49$ eV. An electron accelerated from rest through V volts gains V electronvolts, so 1 keV $= 1.60 \times 10^{-16}$ J and 1 MeV $= 1.60 \times 10^{-13}$ J.

Photon momentum

A photon has no mass, but it does carry **momentum**:

$$p = \frac{E}{c} \quad \text{and, since } E = \frac{hc}{\lambda}, \quad p = \frac{h}{\lambda}$$

The green photon has $p = \dfrac{3.98 \times 10^{-19}}{3.00 \times 10^{8}} = 1.33 \times 10^{-27}$ N s. Never use $p = mv$ for a photon.

When light hits a surface, its photons' momentum changes, so the light **pushes** on the surface (force = rate of change of momentum):

- a photon **absorbed** loses all its momentum: change $= p$;
- a photon **reflected** straight back goes from $+p$ to $-p$: change $= 2p$.

So a beam of power P all absorbed exerts $F = N \times p = \dfrac{P}{E} \times \dfrac{E}{c} = \dfrac{P}{c}$; all reflected, $\dfrac{2P}{c}$. Dividing by the beam's area gives the **radiation pressure**.

The photoelectric effect

Shine electromagnetic radiation on a clean metal surface and electrons may be emitted: the **photoelectric effect**. The emitted electrons are **photoelectrons**. Experiments show:

- **No electrons at all** below a certain frequency, the **threshold frequency** f_0, however intense the radiation. Above it, electrons come off at once, however weak the radiation.
- Above f_0, the electrons have a spread of kinetic energies up to a **maximum**, which rises with frequency but **does not depend on intensity**.
- The number emitted per second (the **photoelectric current**) is **proportional to the intensity**.

A wave model can't explain these: a wave's energy arrives continuously, so a bright enough beam of any frequency should eventually free electrons. The **photon model** explains them all:

1. **One photon gives all its energy to one electron.** Energy is absorbed a whole photon at a time, never in parts.
2. To escape, an electron needs at least the **work function energy** Φ: the **minimum energy needed to remove an electron from the surface** of the metal. Each metal has its own Φ.
3. If $hf < \Phi$, no single photon has enough energy, so **no** electron escapes, whatever the number of photons. The threshold is where $hf_0 = \Phi$.
4. If $hf > \Phi$, the energy left over becomes kinetic energy. Electrons from just at the surface lose the least, so they have the **maximum** kinetic energy; electrons from deeper lose some energy on the way out and come off slower.

Energy conservation for the fastest electrons gives **Einstein's photoelectric equation**:

$$hf = \Phi + \tfrac{1}{2}mv_{\max}^2$$

A 3.0 eV photon on a metal with $\Phi = 2.30$ eV frees electrons with at most $3.0 - 2.30 = 0.70$ eV of kinetic energy.

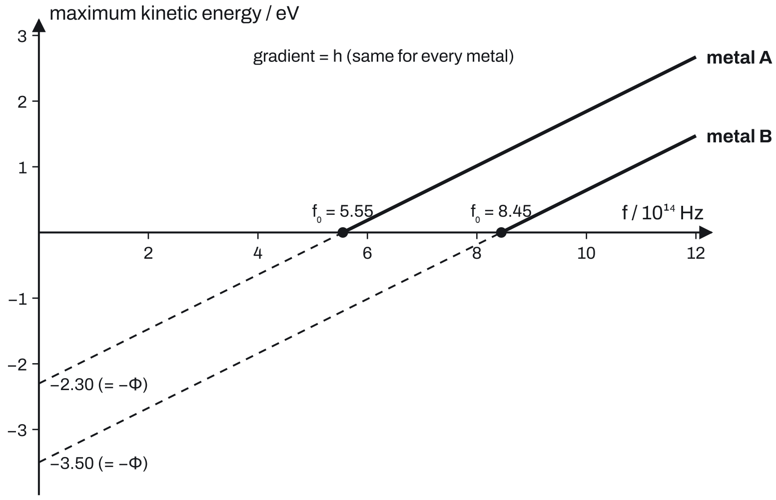
Threshold frequency and threshold wavelength. The **threshold frequency** f_0 is the **minimum frequency** of radiation that releases electrons from the surface; the **threshold wavelength** λ_0 is the **maximum wavelength** that does:

$$f_0 = \frac{\Phi}{h} \qquad \lambda_0 = \frac{c}{f_0} = \frac{hc}{\Phi}$$

Why intensity changes the current but not the maximum kinetic energy. Raising the intensity at the same frequency means **more photons per second**, each with the **same energy** hf. Each photon still frees at most one electron with the same maximum energy $hf - \Phi$; there are just more of them, so the current rises in proportion. To change the maximum kinetic energy you must change the **frequency**.

The graph. Rearranged, $\tfrac{1}{2}mv_{\max}^2 = hf - \Phi$: a straight line of maximum kinetic energy against f with

- **gradient** $= h$, the same for every metal;
- **intercept on the frequency axis** $= f_0$;
- extended back (dashed), **intercept on the energy axis** $= -\Phi$.



A different metal gives a **parallel** line shifted along the frequency axis; a change in intensity leaves the line **unchanged**. The line does **not** pass through the origin, so the maximum kinetic energy is **not** proportional to the frequency.

Wave–particle duality

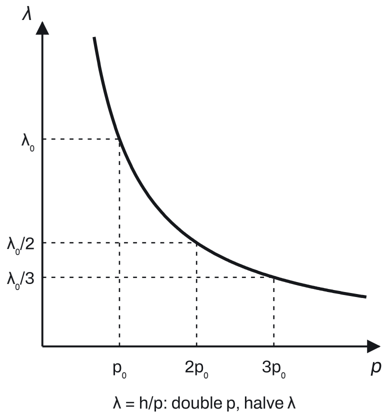
Electromagnetic radiation shows **both** natures:

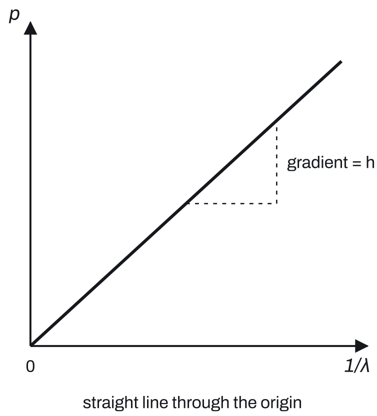
- **wave**: diffraction and interference (Superposition);
- **particle**: the photoelectric effect.

Wave–particle duality is the idea that goes both ways: electromagnetic waves can behave like particles, **and moving particles can behave like waves**. In 1924 de Broglie suggested that every **moving** particle has a wavelength linked to it, its **de Broglie wavelength**:

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

p is the particle's momentum. More momentum means a **shorter** wavelength: doubling p halves λ. A particle at rest has no de Broglie wavelength.





The wavelength only shows up when the particle meets a gap or obstacle about the **same size** as λ. A 70 kg person walking at 1.5 m s^{-1} has $\lambda = \dfrac{6.63 \times 10^{-34}}{70 \times 1.5} = 6.31 \times 10^{-36}$ m, far smaller than a doorway (or even a nucleus), so people never diffract noticeably.

Electron diffraction: evidence for waves

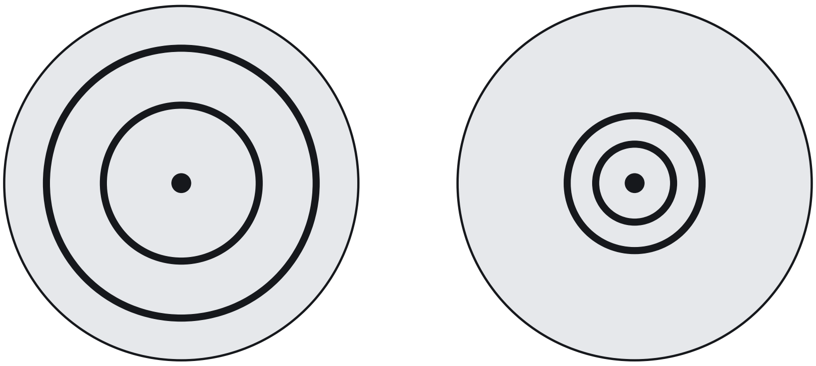
Electrons are accelerated through a high p.d. in a vacuum tube and sent through a very **thin crystal of graphite**. On a fluorescent screen beyond it (the screen glows where electrons land) you see a **bright central spot surrounded by bright concentric rings**.

- The beam **spreads out** after the crystal: that is **diffraction**.
- The bright rings and the dark gaps between them are where the diffracted waves meet **in phase** and **out of phase**: an **interference** pattern.
- Diffraction and interference are wave behaviour, so the pattern shows that **moving electrons behave as waves**. It is evidence of their **wave** nature only (not of a particle nature).
- It works because the **spacing between atoms** in the crystal (about 10^{-10} m) is similar to the electrons' de Broglie wavelength. The layers of atoms act like a diffraction grating.

An electron accelerated from rest through a p.d. V gains kinetic energy $qV = \frac{1}{2}mv^2$, so

$$v = \sqrt{\frac{2qV}{m}} \qquad p = mv = \sqrt{2qVm} \qquad \lambda = \frac{h}{\sqrt{2qVm}}$$

Raise the accelerating p.d. and the electrons have more momentum, so a **shorter** de Broglie wavelength. They diffract through **smaller angles**, so the rings get **smaller and closer together**. (The central spot is always there.)



higher p.d. → larger momentum → shorter wavelength → rings closer together

Energy levels in atoms

An electron in an **isolated** atom (such as a single hydrogen atom in a gas) can only have certain **discrete** energies: its **energy levels**. It can't have an energy between them.

- The lowest level is the **ground state**; higher ones are **excited states**.
- The levels are **negative**: 0 is the energy of an electron that has just been freed from the atom, so energy must be supplied to remove it. A level at -3.40 eV needs 3.40 eV to free the electron.
- The levels get **closer together** higher up.

When an electron **drops** from a higher level E_1 to a lower level E_2, it emits **one photon** whose energy is exactly the **difference** between the two levels:

$$hf = E_1 - E_2 \qquad \text{so} \qquad \lambda = \frac{hc}{E_1 - E_2}$$

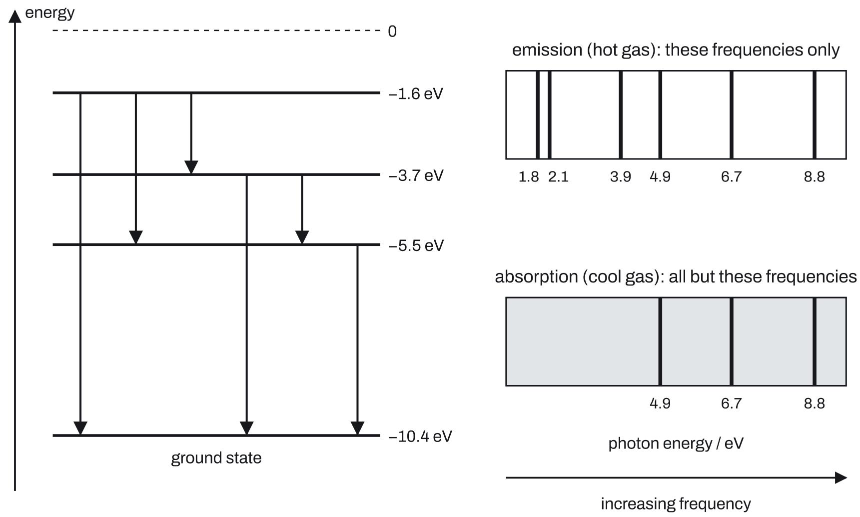
An electron can also move **up** by absorbing a photon, but only one whose energy exactly matches the gap between two levels. A photon with slightly too much or too little energy is not absorbed.

For example, a photon of wavelength 486 nm is emitted when an electron drops to a level at -3.40 eV. Its energy is $\frac{hc}{\lambda} = 2.56$ eV, so the upper level is $-3.40 + 2.56 = -0.842$ eV. (The higher level is less negative.)

Line spectra

Emission spectrum. A hot gas, or a gas with an electric current through it, has atoms with electrons in excited states. As they drop to lower levels they emit photons. There are only a few **discrete energy gaps**, so only a few **discrete photon energies**, and each photon energy means one exact **frequency** (and wavelength). Spread out by a prism or diffraction grating, the light is a set of separate **lines**, one per transition: light at these few frequencies only, and nothing in between. (Seen by eye, they are bright coloured lines on a dark background.)

Absorption spectrum. Pass white light (all frequencies) through a **cool** gas. Electrons, almost all in the ground state, absorb only the photons whose energies match a gap **up from** their level, and are excited. They then drop back down and re-emit the energy, but **in all directions**, so little of it continues along the beam. The transmitted light is a continuous spectrum with a few frequencies **missing**, at the same frequencies as some of the emission lines. (Seen by eye, these are dark lines across the colours.)



Why line spectra are evidence for energy levels: each line is one exact frequency, so each photon has one exact energy ($E = hf$), so each change in the electron's energy is one exact amount. Discrete energy **differences** can only come from discrete energy **levels**.

With four levels there are six possible drops ($3 + 2 + 1$), so up to six emission lines. The **biggest** gap gives the **highest** frequency (shortest wavelength); the smallest gap the lowest frequency (longest wavelength).

Key facts and formulas

"Given" means it is on the data sheet printed in the paper. "Learn it" means you must remember it.

Formula	Status
Photon energy $E = hf$	Learn it
$c = f\lambda$, so $E = \dfrac{hc}{\lambda}$	Learn it
Photons per second $N = \dfrac{P}{hf}$; intensity $=$ power per unit area	Learn it
Photon momentum $p = \dfrac{E}{c} = \dfrac{h}{\lambda}$	Learn it
Force from a beam: absorbed $F = \dfrac{P}{c}$, reflected straight back $F = \dfrac{2P}{c}$; pressure $= \dfrac{F}{A}$	Learn it
$1\ \mathrm{eV} = 1.60 \times 10^{-19}$ J	Learn it

Formula	Status
Photoelectric equation $hf = \Phi + \frac{1}{2}mv_{\max}^2$	Learn it
Threshold $f_0 = \dfrac{\Phi}{h}, \lambda_0 = \dfrac{hc}{\Phi}$	Learn it
de Broglie wavelength $\lambda = \dfrac{h}{p} = \dfrac{h}{mv}$	Learn it
Charge accelerated through V: $qV = \frac{1}{2}mv^2, p = \sqrt{2qVm}$	Learn it
Energy levels $hf = E_1 - E_2$	Learn it
$h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^8$ m s^{-1}, $e = 1.60 \times 10^{-19}$ C, $m_e = 9.11 \times 10^{-31}$ kg, $m_p = 1.67 \times 10^{-27}$ kg, $1\ \mathrm{u} = 1.66 \times 10^{-27}$ kg	Given

How to do it

In the Paper 4 questions we have tagged for this topic (27 different questions, 2021–2025; 11 more appear on two papers), the types came up this often. 19 of the 27 questions mix two or more types, so the counts add up to more than 27.

Question type	Questions
Definitions and statements	16
The photoelectric effect	10
Photon energy, wavelength and photons per second	8
Electron diffraction and wave–particle duality	6
Photon momentum and forces from light	5
de Broglie wavelength calculations and graphs	5
Energy levels and line spectra	5

1. Definitions and statements (16 questions)

Learn these in meaning; each phrase in bold is usually a mark.

- **Photon**: a **quantum** (packet) **of energy** of **electromagnetic radiation**. Say "energy": a photon is not "carried by" radiation, it **is** the radiation's energy.
- **Photoelectric effect**: the **emission of electrons** from a (metal) surface **when electromagnetic radiation falls on it**. Not "when light falls" or "when UV falls": any suitable electromagnetic radiation.

- **Work function energy**: the **minimum** energy (of a photon) needed to **remove an electron from the surface** of the metal.
- **Threshold frequency**: the **minimum frequency** of electromagnetic radiation that causes electrons to be emitted from the surface. **Threshold wavelength**: the **maximum wavelength** that does.
- **de Broglie wavelength**: the wavelength associated with a **moving** particle. A formula is not a definition.
- **Wave–particle duality**: electromagnetic waves can **behave as particles**, and **moving particles can behave as waves**.
- $\lambda = \dfrac{h}{p}$, with h the **Planck constant** and p the particle's momentum; the name of λ is the de Broglie wavelength.

Evidence to quote:

- for the **particle** nature of electromagnetic radiation: the **photoelectric effect**;
- for the **wave** nature of matter (particles): **electron diffraction**;
- for the wave nature of electromagnetic radiation: diffraction or interference of light.

2. The photoelectric effect (10 questions)

1. **Convert** everything to joules (or everything to eV) first. Frequencies are often printed as, for example, " 8.8×10^{14} Hz".
2. **Work function from a threshold**: $\Phi = hf_0 = \dfrac{hc}{\lambda_0}$. For $\Phi = 3.68$ eV: $f_0 = \dfrac{3.68 \times 1.60 \times 10^{-19}}{6.63 \times 10^{-34}} = 8.88 \times 10^{14}$ Hz and $\lambda_0 = 3.38 \times 10^{-7}$ m.
3. **Maximum kinetic energy**: $\frac{1}{2}mv_{\max}^2 = hf - \Phi$. Then $v_{\max} = \sqrt{\dfrac{2E_{k\,\max}}{m_e}}$ if a speed is asked for.
4. **Largest threshold wavelength** from a list of metals: it belongs to the **smallest** work function.

Explaining (the "photon model" questions) use the steps in "The photoelectric effect" above. Every explanation must mention **photons** and **energy**, not just frequency:

- **Why a threshold frequency exists**: one photon frees one electron; photon energy hf depends on frequency; emission only if **photon energy** $\geq$ **work function**; more intensity only adds photons, not energy per photon.
- **Why $E_{k\,\max}$ is independent of intensity; why the current is proportional to it**: see "Why intensity changes the current...".
- **Frequency increased at constant power**: each photon has **more energy**, so $E_{k\,\max}$ **increases**; but the same power now means **fewer photons per second**, so **fewer electrons** per second and a **smaller** current.

Graphs:

- $E_{k\,\max}$ **against** f: a straight line starting on the f-axis at f_0 (zero emission below it), gradient h, dashed extension to $-\Phi$ on the energy axis. State the gradient as **the Planck constant** and the y-intercept as **minus the work function**. Two metals: **parallel** lines, the larger Φ further right. If a metal has twice the work function, it has twice the threshold frequency, and $h = \dfrac{\Phi}{f_0}$.

- **Reading "conclusions" from a given graph**: quote numbers: f_0 from the intercept, h from the gradient, $\Phi = hf_0$ (in J and eV), and that $E_{k\,\max}$ increases linearly (not proportionally) with f.
- $E_{k\,\max}$ **against wavelength**: $E_{k\,\max} = \dfrac{hc}{\lambda} - \Phi$, a **falling curve** reaching zero at λ_0. With $\dfrac{hc}{\lambda_0} = \Phi$: at $\dfrac{\lambda_0}{2}$, $E_{k\,\max} = \Phi$; at $\dfrac{\lambda_0}{3}$, $E_{k\,\max} = 2\Phi$.

Variation: stopping voltage. A reverse p.d. between the plates stops the photocurrent when eV_s equals the maximum kinetic energy: $E_{k\,\max} = eV_s$, so a stopping voltage of 1.2 V means $E_{k\,\max} = 1.2$ eV $= 1.92 \times 10^{-19}$ J. It depends on frequency because the photon energy does. A graph of V_s against f is a straight line of gradient $\dfrac{h}{e}$ crossing the f-axis at f_0.

3. Photon energy, wavelength and photons per second (8 questions)

1. **Energy to wavelength**: $\lambda = \dfrac{hc}{E}$ with E in joules. Convert MeV with $\times 1.60 \times 10^{-13}$, eV with $\times 1.60 \times 10^{-19}$.
2. **Photons per second**: $N = \dfrac{P}{E}$ (power **divided by** photon energy; a plausible answer is huge, like 10^{16} s⁻¹). For a beam of intensity I and area A, first $P = IA$.
3. **Photon energy in eV**: divide the joules by 1.60×10^{-19}.

Variations you will meet:

- **X-ray tube**: electrons accelerated through V each gain eV; the most energetic X-ray photon gets all of it. At 25 kV the maximum photon energy is 25 keV $= 4.00 \times 10^{-15}$ J, so the **minimum** wavelength is $\dfrac{hc}{E} = 4.97 \times 10^{-11}$ m.
- **Gamma photon from a nuclear decay**: the energy released (from the Nuclear physics topic) minus the particle's kinetic energy gives E, then $\lambda = \dfrac{hc}{E}$. Less energy means a **longer** wavelength.
- **Don't** use $\lambda = \dfrac{h}{mv}$ for a photon, or $E = \dfrac{hc}{\lambda}$ for an electron.

4. Electron diffraction and wave–particle duality (6 questions)

1. **Name the effect**: **electron diffraction** (not the photoelectric effect).
2. **What it shows**: the beam **spreads out** (diffraction) and gives bright and dark **rings** (constructive and destructive interference); diffraction is wave behaviour, so **moving electrons behave as waves**. Explain the pattern first, then conclude.
3. **Why a thin crystal**: the spacing between its atoms is **similar to** the electrons' de Broglie wavelength.
4. **Accelerating p.d. increased**: greater speed → greater **momentum** → **shorter** de Broglie wavelength → **smaller** diffraction angles → rings **closer together** (smaller). Keep the central spot when you sketch.

Variations you will meet:

- **Rings further apart in a new pattern**: the wavelength is longer, so the p.d. was **decreased**.
- **Why people don't diffract through doorways**: compare their de Broglie wavelength (about 10^{-36} m) with the width of the doorway (about 1 m): far too small.
- **Describe wave–particle duality**: both halves, as in type 1.

5. Photon momentum and forces from light (5 questions)

1. **Momentum of one photon**: $p = \dfrac{E}{c}$ or $p = \dfrac{h}{\lambda}$. A photon with $p = 1.1 \times 10^{-27}$ N s has $\lambda = \dfrac{h}{p} = 6.03 \times 10^{-7}$ m (orange-red light).
2. **Force**: $F = N \times \Delta p$ (rate of change of momentum), where $\Delta p = p$ for each absorbed photon and $2p$ for each one reflected straight back.
3. **Pressure** $= \dfrac{F}{A}$.

Variations you will meet:

- **"Show that $F = \dfrac{P}{c}$"** for an absorbing surface: $N = \dfrac{P}{E}$ and $p = \dfrac{E}{c}$, so $F = Np = \dfrac{P}{c}$.
- **Half absorbed, half reflected**: $F = \frac{1}{2}Np + \frac{1}{2}N(2p) = \frac{3}{2}Np$.
- **Same intensity, different colour**: bluer photons each have more momentum but there are fewer of them per second; $\dfrac{P}{c}$ is unchanged, so the force and pressure are the **same**.
- **Recoil of a nucleus that emits a gamma photon**: momentum is conserved, so the nucleus moves off with momentum equal to the photon's: $v = \dfrac{p}{M}$. A 1.2 MeV photon from a nucleus of mass 60 u: $p = \dfrac{1.2 \times 1.60 \times 10^{-13}}{3.00 \times 10^{8}} = 6.4 \times 10^{-22}$ N s, $v = \dfrac{6.4 \times 10^{-22}}{60 \times 1.66 \times 10^{-27}} = 6.4 \times 10^{3}$ m s⁻¹, tiny compared with c, so the nucleus's kinetic energy can be ignored.

6. de Broglie wavelength calculations and graphs (5 questions)

1. **Momentum**: $p = mv$; or from an accelerating p.d., $p = \sqrt{2qVm}$ (first $v = \sqrt{\dfrac{2qV}{m}}$).
2. **Wavelength**: $\lambda = \dfrac{h}{p}$.

Variations you will meet:

- **An alpha particle**: its mass is about 4 u $= 4 \times 1.66 \times 10^{-27}$ kg. At 1.5×10^{7} m s⁻¹, $\lambda = \dfrac{6.63 \times 10^{-34}}{4 \times 1.66 \times 10^{-27} \times 1.5 \times 10^{7}} = 6.66 \times 10^{-15}$ m.
- **Sketch λ against p (or v)**: an inverse-proportion curve through the given point, approaching **both** axes without touching them; at double p, half λ (second diagram above). Not a straight line.
- **Sketch p against $\dfrac{1}{\lambda}$**: a straight line **through the origin**; its **gradient is the Planck constant**.
- **Expression for p** in terms of m, q and V: $qV = \frac{1}{2}mv^2$ and $p = mv$ give $p = \sqrt{2qVm}$.

7. Energy levels and line spectra (5 questions)

1. **Explain a single frequency for each transition / lines as evidence for levels**: the electron changes level and emits **one photon**; the photon's **energy equals the difference** between the two levels; photon energy fixes **one frequency** ($E = hf$); discrete lines, so discrete energy differences, so **discrete energy levels**. Use the words photon, photon energy, energy level and frequency, each correctly.
2. **Calculations**: $E_1 - E_2 = hf = \dfrac{hc}{\lambda}$. Convert eV to J. An unknown level: (lower level) $+$ (photon energy) $=$ upper level. Levels are **negative**; keep the sign.
3. **Energy differences from the ground state** in a series of lines to the same level: each line's photon energy **is** that difference; add it to the ground-state energy to get each level.

Variations you will meet:

- **Dark lines in an absorption spectrum**: white light through **cool** gas; photons with exactly a gap's energy are **absorbed**, exciting electrons; these re-emit **in all directions**, so those frequencies are missing from the beam.
- **Placing lines on a spectrum** (increasing frequency to the right): a bigger energy gap gives a line further **right**. The gaps between levels shrink higher up, so lines to the same level crowd together at the high-frequency end.
- **Expressions**: build a level from a known one by adding photon energies hf along a path of transitions, for example $E_3 = E_1 + h(f_A + f_B)$ if one photon f_A takes the electron from level 1 to 2 and f_B from 2 to 3.

Worked examples

The bold codes show where marks are earned, as in Cambridge mark schemes. The number is how many marks.

- **M1** method mark: for a correct method, even if the numbers slip.
- **A1** accuracy mark: for a correct answer; it needs the M mark before it.
- **B1** mark for a correct result on its own, with no method needed.

Example 1

A laser emits green light of wavelength 532 nm with a power of 5.0 mW.

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

(b) Calculate the energy of one photon, in J and in eV. **[3]**

(c) Calculate the number of photons emitted per second. **[1]**

(d) Calculate the momentum of one photon. **[2]**

(e) The beam falls normally on a surface that absorbs all of it. Show that the force on the surface is 1.67×10^{-11} N, and state the force if the surface reflected all the light straight back. **[3]**

Solution

(a) A quantum (packet) of energy **M1** of electromagnetic radiation. **A1**

(b) $E = \dfrac{hc}{\lambda} = \dfrac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{532 \times 10^{-9}}$ **C1** $= 3.74 \times 10^{-19}$ J **A1** $= \dfrac{3.74 \times 10^{-19}}{1.60 \times 10^{-19}} = 2.34$ eV. **A1**

(c) $N = \dfrac{P}{E} = \dfrac{5.0 \times 10^{-3}}{3.74 \times 10^{-19}} = 1.34 \times 10^{16}$ s^{-1}. **A1**

(d) $p = \dfrac{E}{c} = \dfrac{3.74 \times 10^{-19}}{3.00 \times 10^{8}}$ **C1** $= 1.25 \times 10^{-27}$ N s. **A1**

(e) Force $=$ rate of change of momentum; each absorbed photon loses momentum p. **C1** $F = Np = 1.34 \times 10^{16} \times 1.25 \times 10^{-27} = 1.67 \times 10^{-11}$ N (the same as $\dfrac{P}{c} = \dfrac{5.0 \times 10^{-3}}{3.00 \times 10^{8}}$). **A1** Reflected, each photon's momentum changes by $2p$, so $F = 3.33 \times 10^{-11}$ N. **B1**

Example 2

A clean metal surface has a work function energy of 2.30 eV.

(a) State what is meant by the work function energy. **[2]**

(b) Calculate the threshold frequency and the threshold wavelength for the metal. **[3]**

(c) Radiation of wavelength 400 nm falls on the surface. Calculate the maximum kinetic energy and the maximum speed of the emitted electrons. **[4]**

(d) The intensity of the 400 nm radiation is doubled. State and explain the effect on the maximum kinetic energy of the electrons and on the photoelectric current. **[3]**

Solution

(a) The minimum energy **M1** needed to remove an electron from the surface of the metal. **A1**

(b) $\Phi = 2.30 \times 1.60 \times 10^{-19} = 3.68 \times 10^{-19}$ J. **C1** $f_0 = \dfrac{\Phi}{h} = \dfrac{3.68 \times 10^{-19}}{6.63 \times 10^{-34}} = 5.55 \times 10^{14}$ Hz. **A1** $\lambda_0 = \dfrac{c}{f_0} = 5.40 \times 10^{-7}$ m. **A1**

(c) Photon energy $= \dfrac{hc}{\lambda} = \dfrac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{400 \times 10^{-9}} = 4.97 \times 10^{-19}$ J. **C1** $E_{k\,\max} = hf - \Phi = 4.97 \times 10^{-19} - 3.68 \times 10^{-19} = 1.29 \times 10^{-19}$ J (0.808 eV). **A1** $\frac{1}{2} \times 9.11 \times 10^{-31} \times v_{\max}^2 = 1.29 \times 10^{-19}$ **C1**, so $v_{\max} = 5.33 \times 10^{5}$ m s^{-1}. **A1**

(d) The photons still each have the same energy (same frequency), and one photon frees one electron, so the maximum kinetic energy is **unchanged**. **B1** There are twice as many photons per second, **B1** so twice as many electrons per second: the current **doubles**. **B1**

Example 3

The four lowest energy levels of an electron in an isolated atom are -10.4 eV, -5.5 eV, -3.7 eV and -1.6 eV, as in the fourth diagram in "Understand it".

(a) Explain why the emission spectrum of a gas of these atoms consists of separate lines. **[3]**

(b) State the number of different lines that transitions between these four levels can produce. **[1]**

(c) Calculate the shortest and the longest wavelengths of these lines. **[4]**

(d) Atoms in the ground state are exposed to photons of energy 4.9 eV and 5.0 eV. State and explain which photons can be absorbed. **[2]**

Solution

(a) When an electron drops to a lower level it emits one photon **B1** with energy equal to the difference between the two levels. **B1** The levels are discrete, so there are only certain photon energies, and each energy means one frequency ($E = hf$): a line. **B1**

(b) $3 + 2 + 1 = 6$ lines. **B1**

(c) Shortest wavelength: largest gap, $-1.6 - (-10.4) = 8.8$ eV. **C1** $\lambda = \dfrac{hc}{E} = \dfrac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{8.8 \times 1.60 \times 10^{-19}} = 1.41 \times 10^{-7}$ m. **A1** Longest wavelength: smallest gap, $-3.7 - (-5.5) = 1.8$ eV **C1**, so $\lambda = \dfrac{hc}{1.8 \times 1.60 \times 10^{-19}} = 6.91 \times 10^{-7}$ m. **A1**

(d) $-10.4 + 4.9 = -5.5$ eV, an energy level, so the 4.9 eV photons can be absorbed, exciting electrons to -5.5 eV. **B1** 5.0 eV matches no gap from the ground state, so those photons are not absorbed. **B1**

Example 4

Electrons are accelerated from rest through a p.d. of 150 V in a vacuum and then pass through a thin graphite crystal. Rings appear on a fluorescent screen.

(a) State what is meant by the de Broglie wavelength. **[1]**

(b) Show that the speed of the electrons is about 7.3×10^{6} m s^{-1}. **[2]**

(c) Calculate the de Broglie wavelength of the electrons. **[3]**

(d) Explain what the rings show about electrons, and why graphite produces them. **[3]**

(e) The p.d. is increased to 600 V. Calculate the new de Broglie wavelength and describe the change in the pattern. **[3]**

Solution

(a) The wavelength associated with a moving particle. **B1**

(b) $eV = \frac{1}{2}mv^2$: $1.60 \times 10^{-19} \times 150 = \frac{1}{2} \times 9.11 \times 10^{-31} \times v^2$ **C1**, so $v = 7.26 \times 10^6$ m s^{-1}. **A1**

(c) $p = mv = 9.11 \times 10^{-31} \times 7.26 \times 10^6 = 6.61 \times 10^{-24}$ N s. **C1** $\lambda = \dfrac{h}{p} = \dfrac{6.63 \times 10^{-34}}{6.61 \times 10^{-24}}$ **C1** $= 1.00 \times 10^{-10}$ m. **A1**

(d) The beam spreads out and forms bright and dark rings: diffraction and interference, **B1** so moving electrons behave as waves. **B1** The spacing between atoms in graphite is similar to the electrons' wavelength, so they diffract noticeably. **B1**

(e) $p = \sqrt{2eVm}$ is proportional to $\sqrt{V}$: four times the p.d. doubles p **C1**, so $\lambda = \dfrac{1.003 \times 10^{-10}}{2} = 5.01 \times 10^{-11}$ m. **A1** The rings become smaller, closer together (half the radius), around the same central spot. **B1**

Common mistakes

- **Leaving out "energy" or "electromagnetic".** March 2025 and June 2022: many said a photon is "a packet" or "a quantum of radiation" without saying it is a quantum of **energy**. June 2021: some said photons are carried or emitted by the radiation; a photon **is** a packet of electromagnetic energy.
- **Photoelectric explanations with no photons.** June 2021 and November 2021: answers written only in terms of frequency restate the question. The key point is that **one photon's energy** must be at least the **work function**; intensity is the number of photons.
- **Loose definitions.** November 2021 and 2022: the work function is the **minimum** energy to remove an electron **from the surface**, not "to move it to the surface". The photoelectric effect is emission **of electrons**, caused by any electromagnetic radiation, not by one named type, and it is not about electrons changing energy levels in an atom. June 2023: "de Broglie wavelength" needs the word **moving**, and a formula is not a definition.
- **Treating $E_{k\,\max}$ as proportional to f.** June 2022: the line doesn't go through the origin, so it is linear, not proportional. For a different metal, say the **gradient stays the same** and the **intercept changes**; for more intensity, say the **photon energy is unchanged**.
- **Using the frequency as the threshold.** November 2022: the work function was worked out from the incident frequency, ignoring the kinetic energy of the electrons. Use $\Phi = hf - E_{k\,\max}$.
- **Numbers that can't be right.** November 2022 and March 2025: dividing the wrong way gives a photon rate like 10^{-17} s^{-1}; it should be $\dfrac{\text{power}}{\text{photon energy}}$, a huge number. June 2021: a recoil speed many times c should warn you of a slip.
- **The wrong wavelength equation.** November 2021 and March 2021: $\dfrac{h}{p}$ for particles, $\dfrac{hc}{E}$ for photons; don't swap them, and don't use $p = mv$ for a photon (June 2021).
- **Electron diffraction misread.** June 2023 and March 2022: some named the photoelectric effect; many said the electrons "behave as waves" without first saying the pattern shows diffraction; some said diffraction shows both natures. When sketching the new pattern, don't lose the central spot. Explain **why** a shorter wavelength shrinks the rings (smaller diffraction angle).

- **Energy-level wording and signs.** June 2023, November 2022 and March 2023: keep "energy level", "energy difference", "photon energy" and "frequency" distinct. Levels are **negative**: a positive answer for a level is wrong. Give 3 significant figures when the data does.
- **Photon forces.** March 2025: with half the photons absorbed and half reflected, the factor is $\frac{3}{2}$, not 1 or 2.
- λ–p **sketches.** June 2022: a straight line, or a curve that goes flat or vertical, loses marks; draw a smooth curve approaching both axes.

How to get the marks

- **Definitions**: every bold phrase in type 1 is a mark.
- **Calculations**: **C1** is for the right equation with numbers in; **A1** for the answer. Convert eV, keV, MeV, nm and mW first. Give 2 or 3 significant figures, matching the data.
- **"Show that"**: write the starting equation ($E = \frac{hc}{\lambda}$, $qV = \frac{1}{2}mv^2$, $F = \frac{\Delta p}{\Delta t}$), substitute every value, and give one more significant figure than printed.
- **"Explain, with reference to photons"**: use the word **photon** and talk about **energy per photon** and **number of photons**, one point at a time.
- **"State and explain"** (for example a change of frequency or intensity): state the effect, then the physics reason starting from the photon energy.
- **"Explain what can be concluded"** from a pattern: name what you see (spreading, bright and dark rings) and the effect (diffraction), then the conclusion (waves).
- **Graph sketches**: straight or curved, where it meets the axes, same or different gradient, parallel lines, asymptotes. Label lines when there are two.
- **"Suggest"**: a sensible physics reason is enough; compare sizes (wavelength against gap width) when diffraction is involved.

Quick check

1. A gamma-ray photon has an energy of 0.40 MeV. Calculate its wavelength and its momentum.
2. A metal has a work function of 4.50 eV. Calculate its threshold wavelength. Will light of wavelength 500 nm release electrons from it?
3. An electron in an atom drops from a level at -2.10 eV to one at -5.30 eV. Calculate the frequency of the photon emitted.
4. Calculate the de Broglie wavelength of a proton moving at 2.0×10^5 m s^{-1}.
5. The intensity of monochromatic light on a metal is halved, with the frequency unchanged and above the threshold. What happens to the maximum kinetic energy of the photoelectrons, and to the current? Why?

Answers

1. $E = 0.40 \times 1.60 \times 10^{-13} = 6.4 \times 10^{-14}$ J. $\lambda = \dfrac{hc}{E} = \dfrac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{6.4 \times 10^{-14}} = 3.11 \times 10^{-12}$ m. $p = \dfrac{E}{c} = 2.13 \times 10^{-22}$ N s.
2. $\lambda_0 = \dfrac{hc}{\Phi} = \dfrac{6.63 \times 10^{-34} \times 3.00 \times 10^{8}}{4.50 \times 1.60 \times 10^{-19}} = 2.76 \times 10^{-7}$ m (276 nm). No: 500 nm is longer than the threshold wavelength, so each photon has too little energy.
3. Energy difference $= -2.10 - (-5.30) = 3.20$ eV. $f = \dfrac{3.20 \times 1.60 \times 10^{-19}}{6.63 \times 10^{-34}} = 7.72 \times 10^{14}$ Hz.
4. $\lambda = \dfrac{h}{mv} = \dfrac{6.63 \times 10^{-34}}{1.67 \times 10^{-27} \times 2.0 \times 10^{5}} = 1.99 \times 10^{-12}$ m.
5. The maximum kinetic energy is unchanged: each photon still has energy hf and frees one electron. The current halves: half as many photons per second, so half as many electrons per second.

Past questions to try

- **9702/43/O/N/22 Q8**: photons per second, the work function, and the effect of raising the frequency at constant power.
- **9702/43/O/N/23 Q8**: showing $p = \frac{h}{\lambda}$, then the pressure of a beam reflected by a mirror, and red against blue light.
- **9702/42/M/J/23 Q8**: why each transition gives one frequency, placing lines on a spectrum, and an expression for a level.
- **9702/43/M/J/23 Q7**: electron diffraction rings and how they change with a greater accelerating p.d.