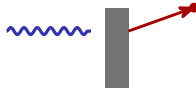


Quantum Physics

A2 Physics ■ Topic 22

A-Level Physics



What we will cover

- 1 Photons: $E = hf$
- 2 The photoelectric effect
- 3 Wave-particle duality
- 4 Energy levels in atoms
- 5 Recap



Light comes in packets

A **photon** is a quantum of EM radiation, travelling at c :

$$E = hf = \frac{hc}{\lambda}, \quad h = 6.63 \times 10^{-34} \text{ J s}$$

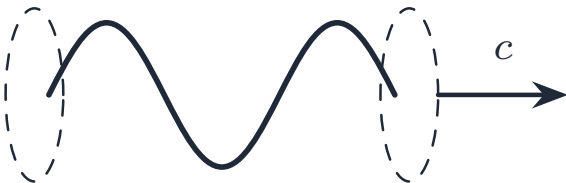
where h is the **Planck constant**. Higher frequency (shorter wavelength) $\Rightarrow$ more energy per photon. Brightness is the **number** of photons per second; colour is the energy of **each** one.

Green light, $\lambda = 500 \text{ nm}$

$$E = hc/\lambda \approx 4.0 \times 10^{-19} \text{ J } (\approx 2.5 \text{ eV})$$

One packet, one electron

A photon is absorbed **whole** or not at all – which is why the effect depends on the photon's frequency and not on how many arrive.



$$E = hf$$

a photon (a packet of light)

The electronvolt, and photon momentum

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

The KE an electron gains moving through 1 V. eV $\rightarrow$ J: multiply; J $\rightarrow$ eV: divide.

A photon has zero rest mass but non-zero momentum:

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

Radiation pressure follows from this.

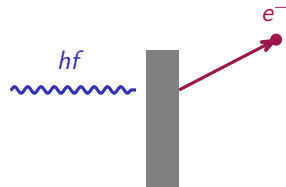


One photon frees one electron

EM radiation of high enough frequency hitting a metal emits **photoelectrons** .

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

Work function $\Phi = hf_0$ is the least energy to free an electron. Below the **threshold frequency** f_0 , **no** electrons come out, however bright.



Worked example – maximum KE

Work function 2.0 eV; photons of 3.5 eV

$$\begin{aligned}\frac{1}{2}mv_{\text{max}}^2 &= hf - \Phi = 3.5 - 2.0 \\ &= 1.5 \text{ eV}\end{aligned}$$

Maximum KE depends **linearly on frequency**,
not on brightness.

Convert Φ to joules before
subtracting if hf is in joules.
A negative answer means you
are below threshold.

Why the wave model fails

A wave model says brightness should set the KE, and any frequency should work given enough time. Experiment says otherwise:

no emission below
 f_0 , however bright

immediate emission at or
above f_0 , even when dim

max KE depends on frequency,
not brightness

the *number* of photoelectrons (the
current) depends on brightness

Why max KE is fixed but current grows with brightness

A brighter beam of the **same frequency** has **more photons per second**, but each still carries hf .

So the maximum KE of any electron is $hf - \Phi$ (set by f only), while the rate of emission (the current) grows with the number of photons, i.e.

Brighter means more photons, not more energetic ones

A brighter beam of the **same frequency** has more photons per second, each still carrying hf . Doubling the brightness doubles the current but does **not** change the maximum KE.



Light is both – and so is matter

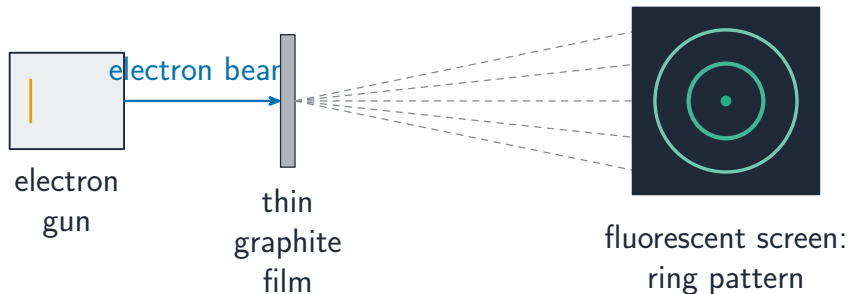
Photoelectric effect $\Rightarrow$ particle. Interference and diffraction $\Rightarrow$ wave. That is **wave-particle duality**. de Broglie: any moving particle has a wavelength

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

Electrons fired at graphite make a ring **diffraction** pattern – only waves diffract, yet electrons do. Faster electron $\Rightarrow$ larger $p \Rightarrow$ shorter $\lambda \Rightarrow$ rings closer together.

Electrons diffract, so electrons are waves

Fire electrons at a thin **crystal lattice** of graphite and they produce **diffraction rings** – a wave effect, from particles with mass. That is **wave-particle duality** : the lattice acts as a natural **diffraction grating** .



Worked example – de Broglie wavelength

Electron accelerated through 2500 V. Find λ .

$E_K = eV$, so $p = \sqrt{2m_e eV}$ and $\lambda = h/p$:

$$\lambda = \frac{h}{\sqrt{2m_e eV}} \approx 2.5 \times 10^{-11} \text{ m}$$

Close to atomic spacings – which is why the electrons diffract off graphite.



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

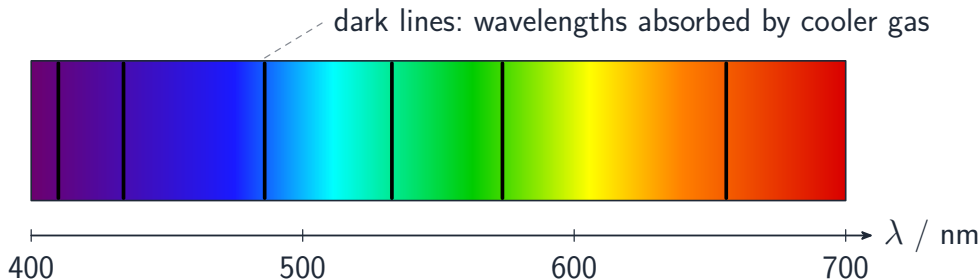
sharp **bright** lines on
a dark background

absorption

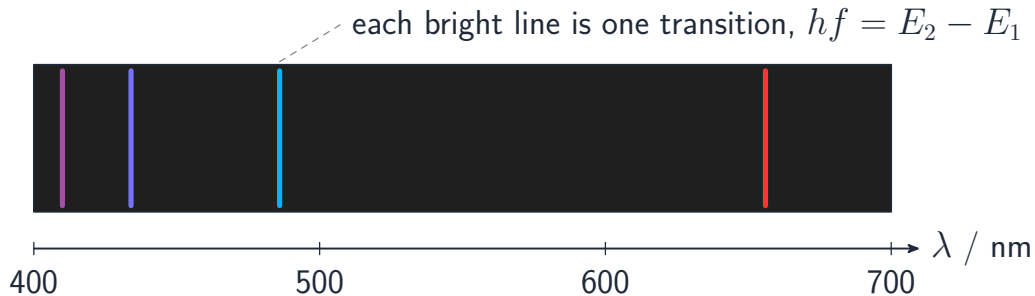
sharp **dark** lines on a
continuous background

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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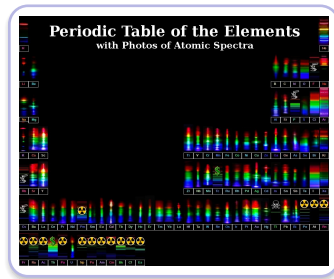
Worked example – a line from a transition

Hydrogen: $n = 3 \rightarrow n = 2$

$$E_3 = -1.51 \text{ eV}, \quad E_2 = -3.40 \text{ eV}$$

$$\Delta E = E_3 - E_2 = 1.89 \text{ eV}$$

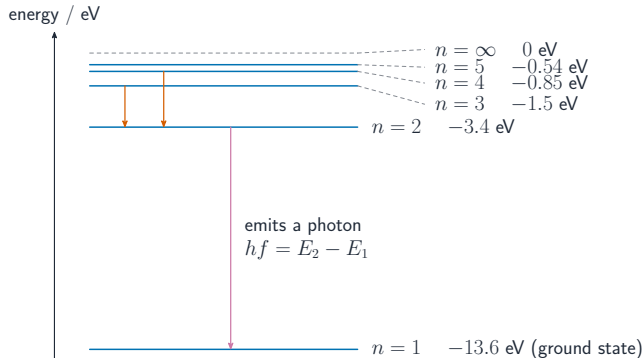
$$\lambda = \frac{hc}{\Delta E} = \frac{1240 \text{ eV nm}}{1.89 \text{ eV}} \approx 656 \text{ nm}$$



The red hydrogen line, at 656 nm.

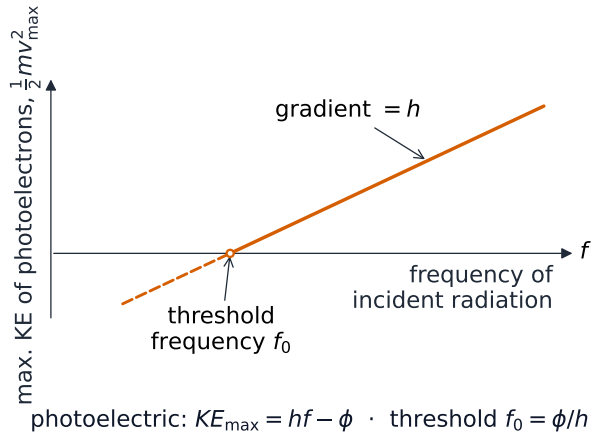
Using $hc = 1240 \text{ eV nm}$ turns a level difference straight into a wavelength.

Energy levels in atoms



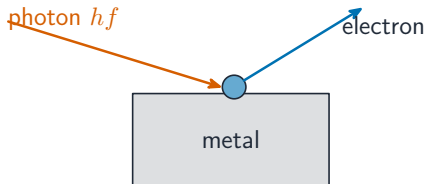
The electron energy levels of hydrogen are discrete and negative, with the ground state at -13.6 eV

Einstein's photoelectric equation



The maximum kinetic energy of photoelectrons rises linearly with frequency, reaching zero at the threshold frequency f_0

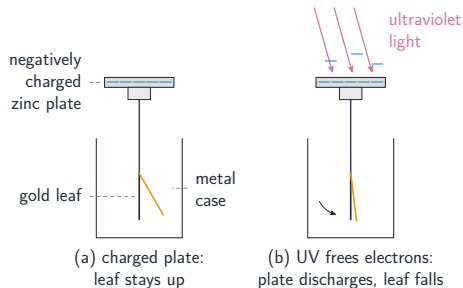
Photoelectric effect



$$hf = \Phi + KE_{\max}$$

(escape energy Φ + leftover KE)

One photon gives its energy hf to one electron: part frees it (the work function Φ), the



A charged zinc plate loses its charge – the gold leaf falls – when ultraviolet light shines on it

One photon gives its energy hf to one electron: part frees it (the work function Φ), the rest is the electron's KE

A field of solar panels



Solar cells use the photoelectric effect to turn light into electricity.

Exam tips

- Photon energy $E = hf = hc/\lambda$; the **photoelectric equation** is $hf = \Phi + \frac{1}{2}mv_{max}^2$.
- The photoelectric effect shows light is **quantised**: below the threshold frequency, no electrons are emitted whatever the intensity.
- **de Broglie** $\lambda = h/p$ gives particles a wavelength; electron diffraction is the evidence.
- Energy levels are discrete; an emitted photon's energy equals the **difference between two levels**.



Topic 22 – key takeaways

1 Photon

$$E = hf = hc/\lambda; p = h/\lambda$$

2 Photoelectric

$$hf = \Phi + E_{k,\max}; \text{ threshold } f_0$$

3 Duality

$$\lambda = h/p - \text{electrons diffract too}$$

4 Levels

$$hf = E_2 - E_1 - \text{line spectra}$$

Check yourself

- 1 Below threshold, does brighter light help?
- 2 What does doubling brightness (same f) do to max KE and to current?
- 3 Faster electron: longer or shorter de Broglie λ ?
- 4 Why is an emission spectrum a set of sharp lines?

Answers 1. no 2. KE unchanged; current doubles 3. shorter 4. energy levels are discrete