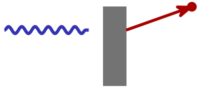
Quantum Physics

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

1 The photon

Light comes in packets

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

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

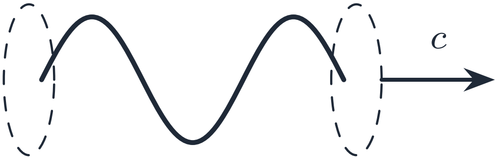
where h is the **Planck constant** 普朗克常数. Higher frequency (shorter wavelength) $\Rightarrow$ more energy per photon. Brightness is the number of photons per second; colour is the energy of each one.

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

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

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

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

The KE an electron gains moving through $1\,\mathrm{V}$. 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.

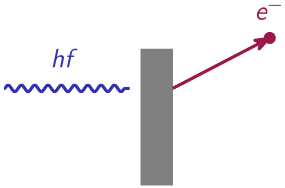
2 Photoelectric effect

One photon frees one electron

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

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

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



Worked example – maximum KE

Work function $2.0\,\mathrm{eV}$; photons of $3.5\,\mathrm{eV}$

$$\tfrac{1}{2}mv_{\max}^2 = hf - \Phi = 3.5 - 2.0$$

$$= 1.5\,\mathrm{eV}$$

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.

3 Wave–particle duality

Light is both – and so is matter

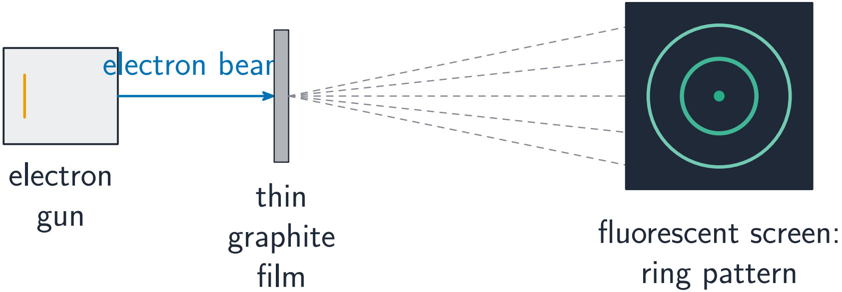
Photoelectric effect $\Rightarrow$ particle. Interference and diffraction $\Rightarrow$ wave. That is **wave–particle duality** 波粒二象性. de Broglie: any moving particle has a wavelength

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

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

Electrons diffract, so electrons are waves

Fire electrons at a thin **crystal lattice** 晶格 of graphite and they produce diffraction rings – a wave effect, from particles with mass. That is **wave–particle duality** 波粒二象性: the lattice acts as a natural **diffraction grating** 衍射光栅.



Worked example – de Broglie wavelength

Electron accelerated through $2500\,\mathrm{V}$. Find λ.

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

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

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

4 Energy levels

Electrons sit on discrete rungs

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

$$hf = E_2 - E_1$$

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** 线状光谱.

emission

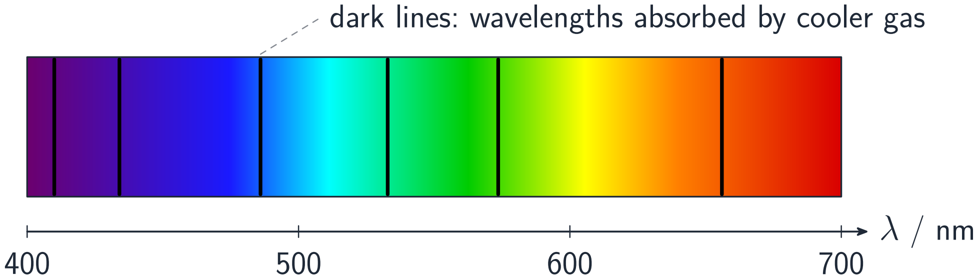
sharp bright lines on a dark background

absorption

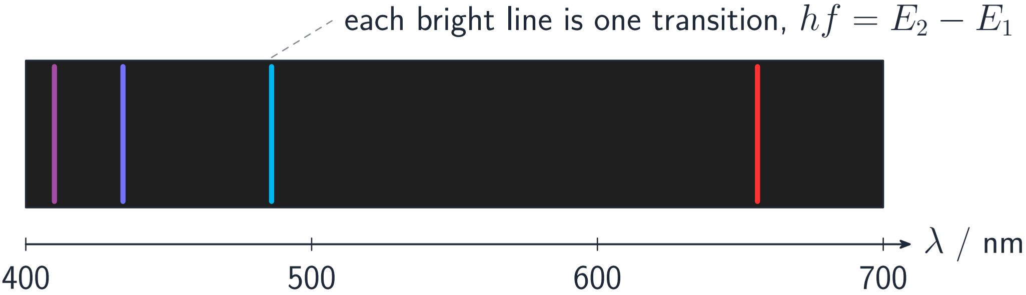
sharp dark lines on a continuous background

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** 吸收光谱 at exactly those frequencies – the dark **Fraunhofer lines** 夫琅禾费线 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:

> $$

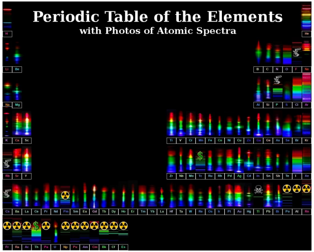
Worked example – a line from a transition

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

$$E_3 = -1.51\,\mathrm{eV}, \qquad E_2 = -3.40\,\mathrm{eV}$$

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

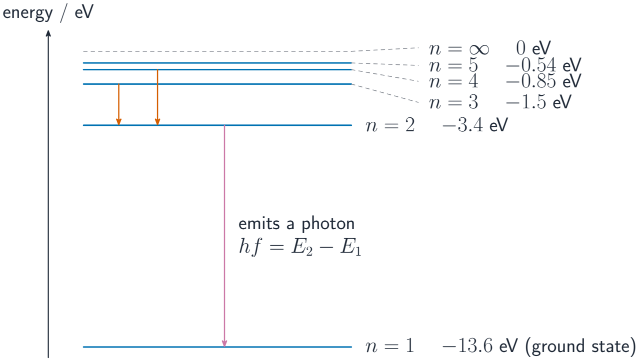
$$\lambda = \frac{hc}{\Delta E} = \frac{1240\,\mathrm{eV\,nm}}{1.89\,\mathrm{eV}} \approx 656\,\mathrm{nm}$$



The red hydrogen line, at $656\,\mathrm{nm}$.

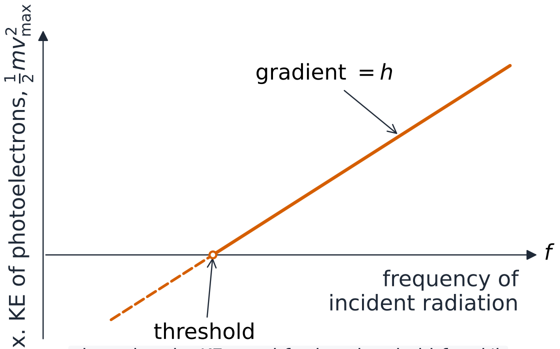
Using $hc = 1240\,\mathrm{eV\,nm}$ turns a level difference straight into a wavelength.

Energy levels in atoms



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

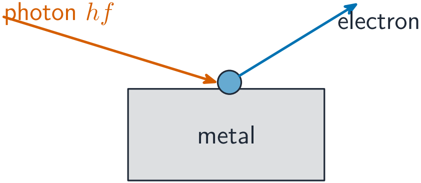
Einstein's photoelectric equation



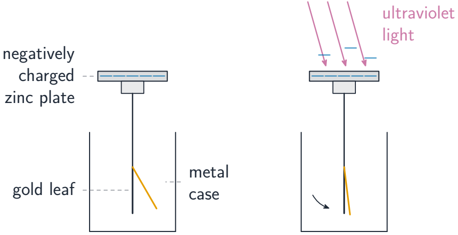
photoelectric: $KE_{\max} = hf - \phi$ · threshold $f_0 = \phi/h$

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

Photoelectric effect



$$hf = \Phi + \mathrm{KE}_{\max}$$
(escape energy Φ + leftover KE)



(a) charged plate: leaf stays up

(b) UV frees electrons: plate discharges, leaf falls

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 i

> 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**.

5 Recap

Topic 22 – key takeaways

1 Photon

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

2 Photoelectric

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

3 Duality

$\lambda = h/p$ – electrons diffract too

4 Levels

$hf = E_2 - E_1$ – 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