

Quantum physics

A-Level Physics 9702 · Topic 22 revision notes · A2

Light as photons, the photoelectric effect and work function, wave-particle duality with de Broglie waves, and discrete energy levels giving line spectra.

14 definitions to learn word for word, 12 equations in their own column, 7 diagrams and graphs. Read it, cover it, test yourself.

1. 22.1 Energy and momentum of a photon
2. 22.2 Photoelectric effect
3. 22.3 Wave-particle duality
4. 22.4 Energy levels in atoms and line spectra

Definitions (mark-scheme wording) Equations Exam traps

22.1 Energy and momentum of a photon

Definitions

Photon: a quantum (discrete packet) of energy of electromagnetic radiation.

Electronvolt (eV): the energy gained by an electron when it is accelerated through a potential difference of 1 V ($1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$).

Planck constant (h): the constant relating photon energy to frequency: $h = E/f = 6.63 \times 10^{-34} \text{ J s}$.

Key points

- ✓ Photon energy is **proportional to frequency** and **inversely proportional to wavelength**.
- ✓ Intensity of a beam = number of photons per second per unit area $\times$ energy of each photon.
- ✓ A photon has **no mass** but carries **momentum** $p = E/c$; absorbing or reflecting light exerts a force.
- ✓ eV to J: **multiply by e** (1.60×10^{-19}); J to eV: divide by e.
- ✓ An electron accelerated through V gains kinetic energy **eV**.
- ✓ Visible photons have energies of roughly **1.8 to 3.1 eV** (red to violet).

Equations

$$E = hf$$

photon energy
J

$$E = hc / \lambda$$

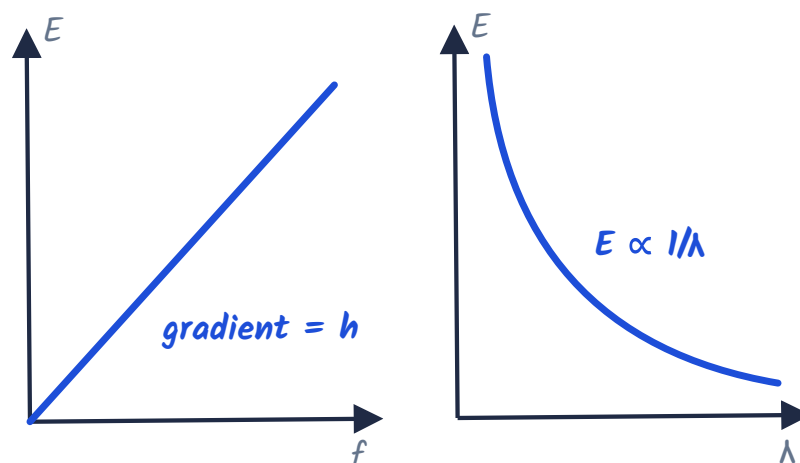
photon energy from wavelength ($c = 3.00 \times 10^8 \text{ m s}^{-1}$)
J

$$p = E / c = h / \lambda$$

momentum of a photon
 kg m s^{-1}

$$E = eV$$

energy gained by charge e through p.d. V
J



Photon energy against frequency is a straight line through the origin (gradient h); against wavelength it is an inverse curve.

Watch out!

- ! Short wavelength means **high** photon energy (UV, X-rays), not low.
- ! Convert eV to J before using $E = hf$ with h in J s.

22.2 Photoelectric effect

Definitions

Photoelectric effect: the emission of electrons from the surface of a metal when electromagnetic radiation of high enough frequency falls on it.

Work function (Φ): the minimum energy needed to remove an electron from the surface of a metal.

Threshold frequency (f_0): the minimum frequency of electromagnetic radiation that will release electrons from the surface of a metal.

Threshold wavelength (λ_0): the maximum wavelength of electromagnetic radiation that will release electrons from the surface of a metal.

Equations

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

Einstein's photoelectric equation

$$\Phi = hf_0 = hc / \lambda_0$$

work function and threshold

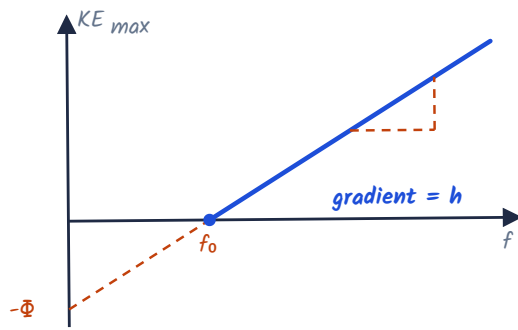
$$eV_s = \frac{1}{2}mv_{\max}^2$$

stopping potential measures $KE_{\max}$

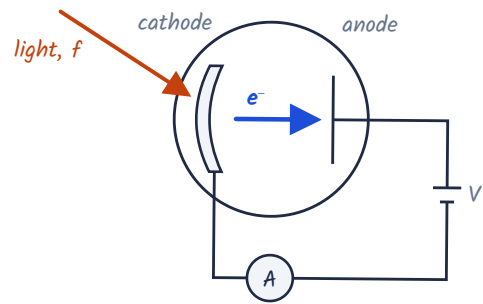
Key points

- ✓ Each electron absorbs **one photon**: all of the photon energy or none (one-to-one interaction).
- ✓ Below f_0 **no electrons** are emitted, however intense the light; above f_0 emission is **instantaneous**.
- ✓ Max KE depends on **frequency** only, not intensity: photon energy minus work function.
- ✓ Electrons deeper in the metal lose extra energy, so emitted KE ranges **from 0 up to $KE_{\max}$** .
- ✓ Photoelectric **current** $\propto$ **intensity** (more photons per second, more electrons per second), for $f > f_0$.
- ✓ These features show light is a **particle** (photon); a wave model predicts emission at any frequency after a delay.

- ✓ Stopping potential V_s : the p.d. that just stops the fastest electrons,
so $eV_s = KE_{max}$



KE_{max} against f : straight line, gradient h , x-intercept f_0 , extrapolated y-intercept $-\Phi$. Every metal gives a parallel line.



Photocell: light on the cathode releases electrons; the reverse p.d. that makes the current just zero is the stopping potential.

Watch out!

- ! Greater intensity gives **more** photoelectrons (bigger current), never faster ones.
- ! The equation uses the **maximum** KE; most emitted electrons have less.
- ! Threshold **wavelength** is a maximum, threshold **frequency** a minimum.

22.3 Wave-particle duality

Definitions

Wave-particle duality: the idea that light and matter show both wave properties and particle properties.

De Broglie wavelength: the wavelength associated with a moving particle: $\lambda = h/p$, where p is its momentum.

Key points

- ✓ Light as a **particle**: the photoelectric effect. Light as a **wave**: diffraction and interference.
- ✓ **Electron diffraction** is evidence that particles (electrons) behave as waves.
- ✓ Electrons through thin **graphite**: layer spacing ($\sim 10^{-10}$ m) is similar to λ , giving diffraction rings on the screen.
- ✓ Higher accelerating p.d. gives faster electrons, **shorter λ** , so **smaller rings**.
- ✓ Electron accelerated through V : $\frac{1}{2}mv^2 = eV$, so $p = \sqrt{2meV}$.
- ✓ Diffraction is only noticeable when λ is comparable with the gap or spacing.

Equations

$$\lambda = h / p$$

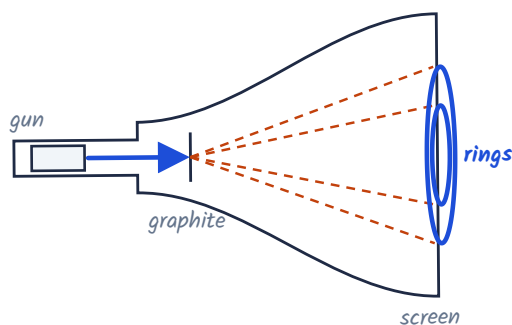
de Broglie wavelength
 m

$$\lambda = h / (mv)$$

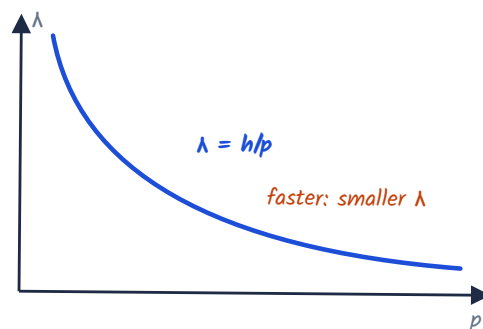
for a particle of mass m , speed v (non-relativistic)
 m

$$p = \sqrt{2meV}$$

momentum of electron accelerated through V
 $kg \ m \ s^{-1}$



Electron diffraction tube: electrons from the gun pass through graphite and form concentric rings on the fluorescent screen.



De Broglie wavelength against momentum: an inverse relationship ($\lambda p = h$).

Watch out!

- ! Faster electrons have **shorter** wavelengths and diffract **less**: the rings shrink.
- ! Use $p = mv$ for the particle, not E/c (that is for photons only).

22.4 Energy levels in atoms and line spectra

Definitions

Energy level: one of the discrete (quantised) energies that an electron in an isolated atom can have.

Ground state: the lowest energy level of an atom.

Excitation: the promotion of an electron to a higher energy level by absorbing a photon of exactly the right energy (or by collision).

Ionisation energy: the minimum energy needed to remove an electron from the ground state of the atom completely (to the zero level).

Line spectrum: a spectrum consisting of discrete wavelengths only, each corresponding to a transition between two energy levels.

Equations

$$hf = E_1 - E_2$$

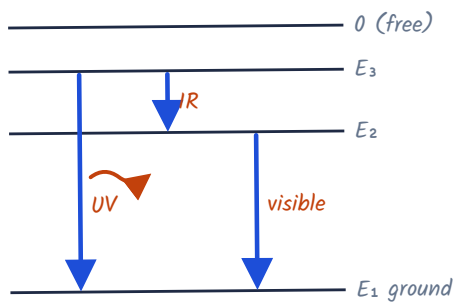
photon energy = difference between levels ($E_1 > E_2$)
J

$$\lambda = hc / (E_1 - E_2)$$

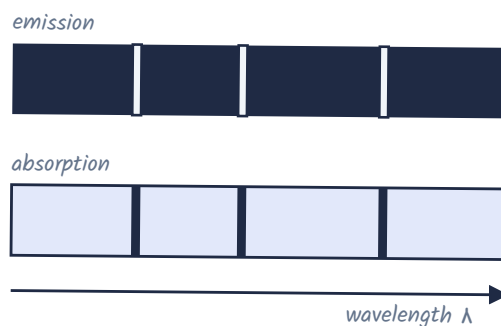
wavelength of the spectral line
m

Key points

- ✓ Energy levels are **negative**; zero corresponds to a free electron at infinity. Levels crowd together near the top.
- ✓ Downward transition: **photon emitted** with energy exactly equal to the gap. Upward: photon of exactly that energy absorbed.
- ✓ Discrete levels give **discrete photon energies**, so discrete wavelengths: line spectra, not continuous.
- ✓ **Emission spectrum:** bright lines on a dark background, from a hot low-pressure gas.
- ✓ **Absorption spectrum:** dark lines in a continuous spectrum, where white light passes through cooler gas.
- ✓ Absorption lines are at the **same wavelengths** as that element's emission lines; re-emission is in all directions.
- ✓ Biggest gap = highest energy photon = **shortest wavelength** line.
- ✓ Number of possible lines from level n down: $n(n-1)/2$.



Energy levels: a drop from E_3 to E_1 emits one photon with $hf = E_3 - E_1$; the longest arrow gives the shortest wavelength.



Emission lines (bright on dark) and absorption lines (dark on a continuous spectrum) at the same wavelengths for one element.

Watch out!

- ! Photon energy is the **difference** between two levels, not the value of one level.
- ! Subtracting negative levels: $-1.5 \text{ eV} - (-3.4 \text{ eV}) = +1.9 \text{ eV}$. Mind the signs.
- ! Only photons of **exactly** a gap energy are absorbed (unless they ionise the atom).