Quantum physics

Photons and E = hf, the electronvolt, photon momentum, the photoelectric effect and Einstein's equation, threshold frequency and work function, wave-particle duality and the de Broglie wavelength, and energy levels with line spectra.

22.1 Energy and momentum of a photon

Electromagnetic radiation has a particulate nature. A **photon** is a quantum of electromagnetic energy: a discrete packet of it.

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

where $h = 6.63 \times 10^{-34}$ J s is the Planck constant.

The electronvolt

An **electronvolt (eV)** is the energy gained by an electron accelerated through a p.d. of 1 V:

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

Photon momentum

A photon has no rest mass, but it does have momentum:

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

Combining this with $E = hc/\lambda$ gives $p = h/\lambda$.

> TRY IT
>
> **Find the energy of a 500 nm photon, in J and eV, and its momentum.** $E = (6.63 \times 10^{-34} \times 3.0 \times 10^{8})/(5.0 \times 10^{-7}) = 4.0 \times 10^{-19}$ J, which is 2.5 eV. $p = E/c = 1.3 \times 10^{-27}$ N s.

22.2 Photoelectric effect

Electrons may be emitted from a metal surface when it is illuminated with electromagnetic radiation. These are **photoelectrons**.

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Observations and terms

- **Threshold frequency** f_0: the minimum frequency needed to emit electrons from the surface. Below it, none are emitted, however intense the radiation.
- **Threshold wavelength** λ_0: the maximum wavelength that will emit electrons.
- **Work function** Φ: the minimum energy needed to remove an electron from the surface. $\Phi = hf_0$.
- Emission is instantaneous, even in faint light.

Einstein's equation

One photon gives all of its energy to one electron. If it has enough, the electron escapes. Any remaining energy is its kinetic energy:

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

Electrons deeper in the metal lose energy on the way out, so this is the **maximum** kinetic energy.

A graph of $E_{K,\max}$ against f has gradient h, x-intercept f_0, and an extrapolated y-intercept of $-\Phi$. All metals have the same gradient.

Why intensity does not change the maximum kinetic energy

Increase	Effect	Why
Intensity (same frequency)	more photons per second, so more electrons per second, so **larger current**	the photoelectric current is proportional to intensity
Frequency	**larger maximum kinetic energy**	each photon has more energy; a single electron only ever absorbs a single photon

TRY IT

Light of 400 nm falls on a metal of work function 2.0 eV. Find the maximum kinetic energy.
Photon energy $= hc/\lambda = 4.97 \times 10^{-19}$ J $= 3.1$ eV. $E_K = 3.1 - 2.0 = 1.1$ eV.

22.3 Wave-particle duality

- The **photoelectric effect** shows the **particulate** nature of electromagnetic radiation.
- **Interference and diffraction** show its **wave** nature.

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Electron diffraction

Electrons fired at a thin slice of graphite produce rings on a fluorescent screen, which is a diffraction pattern. Diffraction is a wave property, so **particles can behave as waves**. Faster electrons have a smaller wavelength, so the rings get closer together.

The de Broglie wavelength

Any moving particle has an associated wavelength:

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

For an electron accelerated through a p.d. V: $\frac{1}{2}mv^2 = eV$, so $p = \sqrt{2meV}$.

> **TRY IT**
>
> **Find the de Broglie wavelength of an electron travelling at 2.0×10^6 m/s.** $\lambda = 6.63 \times 10^{-34}/(9.11 \times 10^{-31} \times 2.0 \times 10^6) = 3.6 \times 10^{-10}$ m, which is about the spacing of atoms in a crystal, and that is why diffraction is seen.

22.4 Energy levels in atoms and line spectra

Electrons in isolated atoms can only have certain **discrete energies**. These levels are negative, with zero meaning the electron has just escaped.

When an electron drops between levels, it emits one photon:

$$hf = E_1 - E_2$$

- **Emission line spectrum:** bright lines on a dark background, from a hot, low-pressure gas. Excited electrons fall to lower levels and emit only particular photon energies.
- **Absorption line spectrum:** dark lines on a continuous spectrum, when white light passes through a cool gas. Atoms absorb only the photons that exactly match a gap between levels, then re-emit them in all directions.

Since levels are discrete, the photon energies are discrete, which gives lines rather than a continuous spectrum.

> **NOTE**
>
> Exam tip: count transitions carefully: from level 3, an electron can drop 3→2, 3→1 and 2→1, which gives three lines. The largest energy gap gives the shortest wavelength. Convert eV to J before using $E = hc/\lambda$.

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