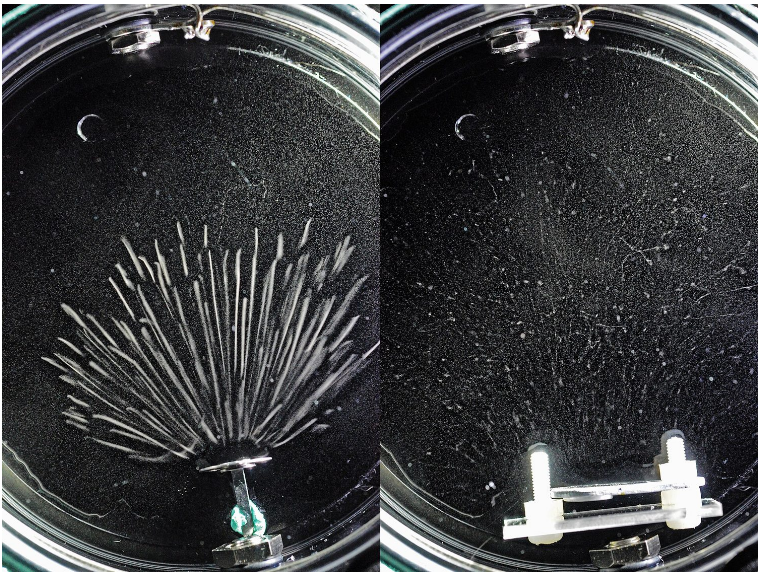
Modern Physics

AP Physics 2

Quantum Theory and Wave-Particle Duality

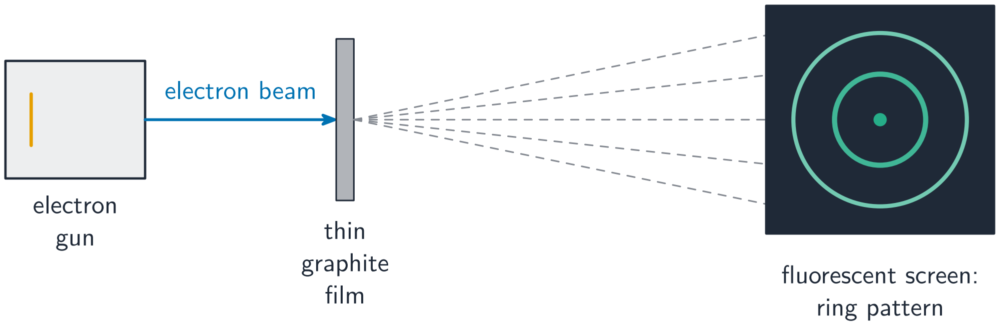


A cloud chamber: modern physics tracks charged particles from radioactive decays

At tiny scales, energy comes in discrete packets called **quanta** 量子. Light is carried by **photons** 光子, each with energy set by its frequency:

$$E = hf,$$

where h is Planck's constant. **Wave–particle duality** 波粒二象性: light and matter each show both wave behavior (interference, diffraction) and particle behavior (photons, electrons as localized hits). A particle also has a **matter wavelength** $\lambda = \frac{h}{p}$, and particles genuinely produce interference - a variation of Young's **double-slit experiment** 双缝实验 done with electrons builds up the same fringe pattern as light.



Electrons form a diffraction pattern, showing that particles have a wave nature

Worked example. Find the energy of a photon of orange light with frequency 5.0×10^{14} Hz ($h = 6.63 \times 10^{-34}$ J s): $E = hf = 6.63 \times 10^{-34} \times 5.0 \times 10^{14} = 3.3 \times 10^{-19}$ J, which is about 2.1 eV (dividing by 1.6×10^{-19}). Visible-light photons carry a few electronvolts – just right to trigger the chemistry of vision and photosynthesis.

The Bohr Model of Atomic Structure

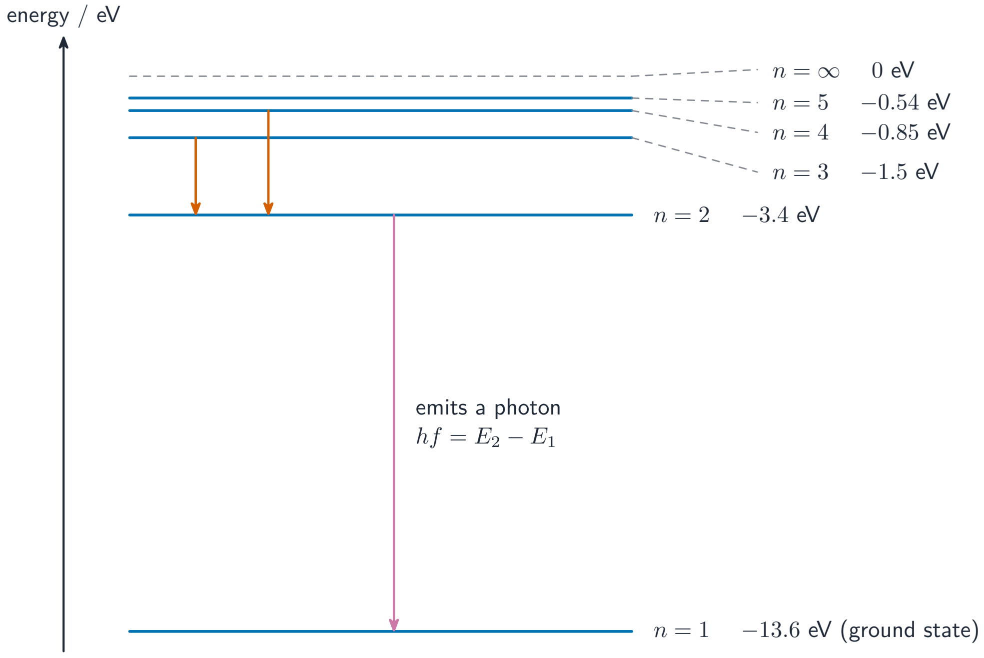
The **Bohr model** 玻尔模型 pictures electrons orbiting the nucleus only in certain allowed **energy levels** 能级. An electron can jump between levels only by absorbing or emitting a photon whose energy exactly matches the gap:

$$E_{\text{photon}} = |E_{\text{final}} - E_{\text{initial}}|.$$

Because the levels are discrete, only specific photon energies are allowed.

Emission and Absorption Spectra

- An **emission spectrum** 发射光谱 is the set of bright lines given off when electrons drop to lower levels – each line a specific wavelength.
- An **absorption spectrum** 吸收光谱 is the set of dark lines where those same wavelengths are absorbed from a continuous source.



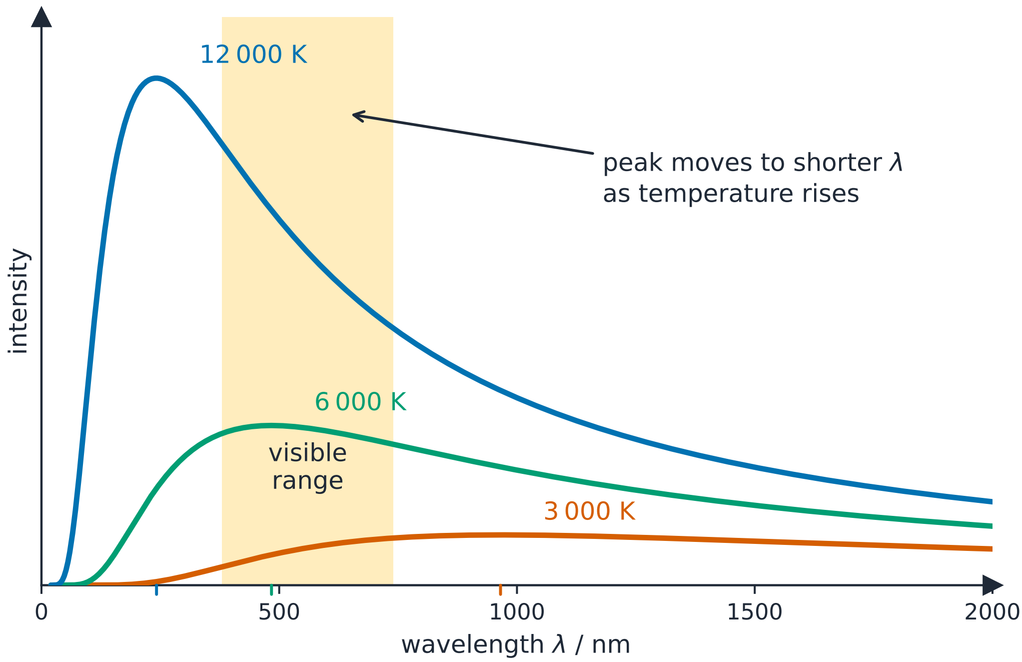
The discrete energy levels of hydrogen produce a line spectrum

The line pattern is a **fingerprint** of the element, since every element has its own energy levels.

Hydrogen's emission spectrum: each bright line is light from an electron dropping between fixed energy levels

Blackbody Radiation

A **blackbody** 黑体 emits a continuous spectrum that depends only on its temperature. Hotter objects glow brighter and peak at **shorter** wavelengths (red-hot to white-hot to blue-hot). Explaining this spectrum required quantized energy – a founding problem of quantum theory.



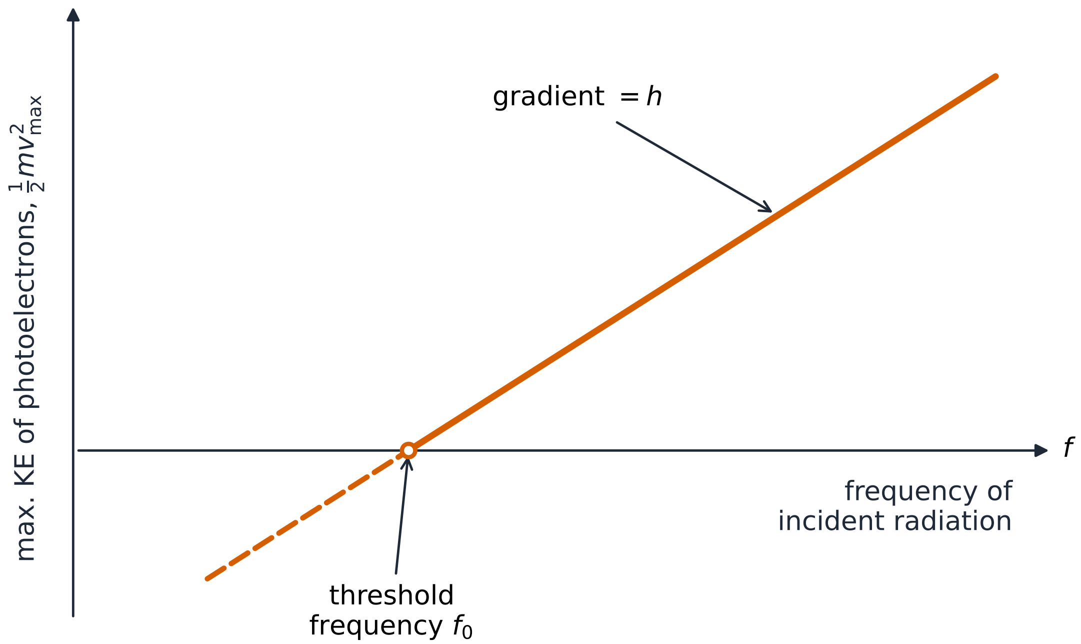
A hotter black body radiates more, and its peak shifts to shorter wavelengths

The Photoelectric Effect

Shining light on a metal can eject electrons – the **photoelectric effect** 光电效应. Key facts (which only the photon picture explains): electrons come out only if the photon's frequency exceeds a threshold, no matter how bright a dimmer, lower-frequency light is. Energy conservation gives

$$K_{\max} = hf - \phi,$$

where ϕ is the metal's **work function** 逸出功 (the energy to free an electron).



The maximum kinetic energy of photoelectrons rises linearly with frequency

Worked example. Light of frequency 8.0×10^{14} Hz falls on a metal with work function $\phi = 3.0 \times 10^{-19}$ J. The most energetic electrons come off with

$$K_{\max} = hf - \phi = (6.63 \times 10^{-34} \times 8.0 \times 10^{14}) - 3.0 \times 10^{-19} = 5.3 \times 10^{-19} - 3.0 \times 10^{-19} = 2.3 \times 10^{-19} \text{ J}.$$

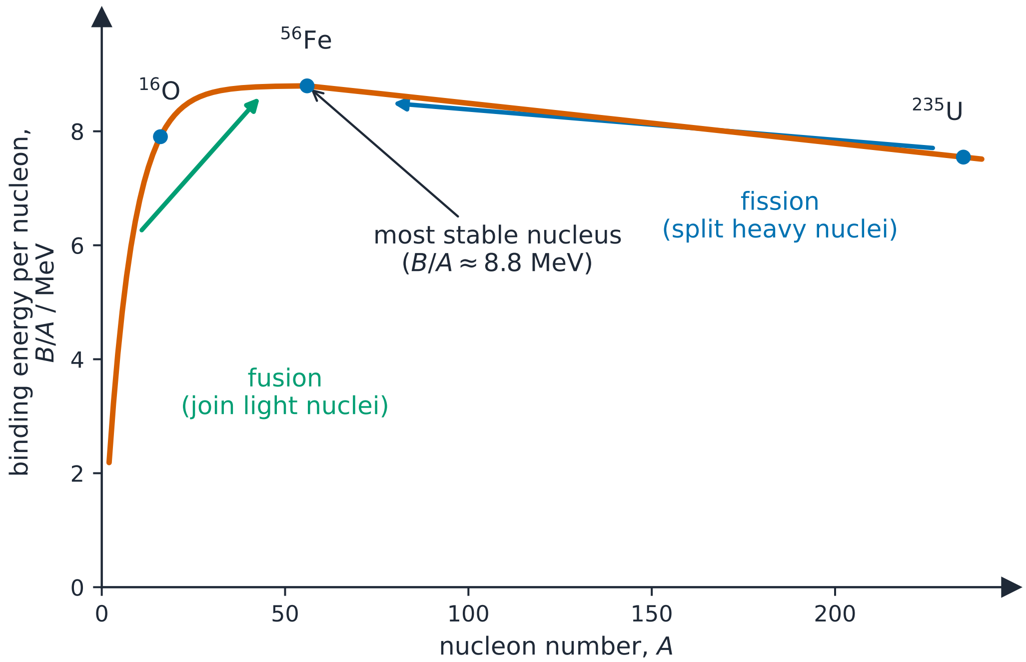
Below the threshold frequency ϕ/h, $K_{\max}$ would be negative – meaning no electrons escape at all, however bright the light.

Compton Scattering

In **Compton scattering** 康普顿散射, a photon collides with an electron like two particles, transferring some energy and momentum. The scattered photon comes out with **less energy** (longer wavelength). This is direct evidence that photons carry momentum and behave as particles.

Fission, Fusion, and Nuclear Decay

The **nucleus** 原子核 stores enormous energy. **Fission** 裂变 splits a heavy nucleus into lighter ones, releasing energy (nuclear reactors, bombs). **Fusion** 聚变 joins light nuclei into a heavier one (the Sun's power). Both release energy because the products have slightly **less mass**, converted by $E = mc^2$.



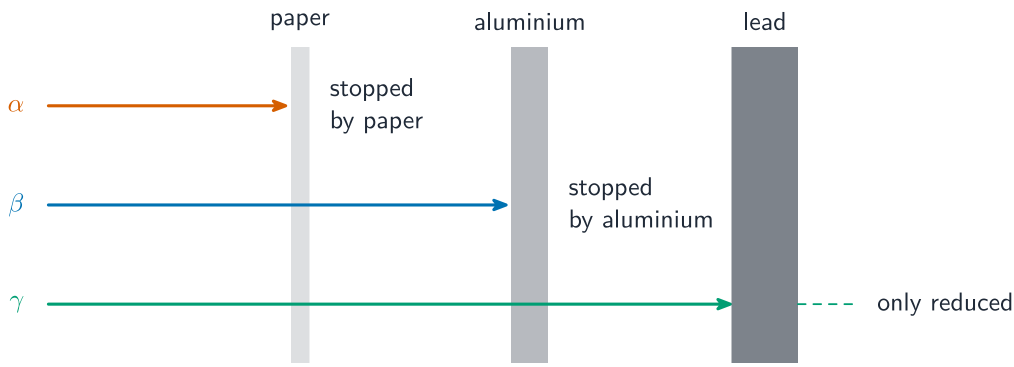
Binding energy per nucleon peaks near iron, so both fusion and fission can release energy

Worked example. Even a tiny mass converts to a huge energy. If a nuclear reaction loses 1.0×10^{-3} kg of mass, it releases $E = mc^2 = 1.0 \times 10^{-3} \times (3.0 \times 10^8)^2 = 9.0 \times 10^{13}$ J – roughly the energy of 20 000 tonnes of TNT.

A nuclear power station: fission of heavy nuclei releases the energy that drives the plant

Types of Radioactive Decay

Unstable nuclei undergo **radioactive decay** 放射性衰变, emitting:



The penetrating power of alpha, beta, and gamma radiation

- **Alpha decay** 阿尔法衰变 (α): a helium nucleus – mass number drops by 4.
- **Beta decay** 贝塔衰变 (β) comes in two kinds. In **beta-minus** (β^-) a neutron becomes a proton, emitting an electron and an **antineutrino** 反中微子: $n \to p + e^- + \bar{\nu}$. In **beta-plus** ($\beta^+$) a proton becomes a neutron, emitting a **positron** 正电子 and a **neutrino** 中微子: $p \to n + e^+ + \nu$.
- **Gamma decay** 伽马衰变 (γ): a high-energy photon – the nucleus sheds excess energy.

The neutrino and antineutrino (symbols ν, $\bar{\nu}$) are tiny, chargeless, almost-massless particles that carry off energy and keep beta decay balanced. Decay is random, but a sample halves every **half-life 半衰期**: after each half-life, half of the remaining nuclei have decayed. Every decay equation conserves three quantities: **nucleon number** (mass number), **charge**, and **lepton number 轻子数** – an electron or neutrino counts as $+1$ lepton, a positron or antineutrino as -1, and the totals must match on both sides.

Worked example. A radioactive sample has a half-life of 8.0 days. What fraction is left after 24 days? That is $24/8.0 = 3$ half-lives, so the fraction remaining is $\left(\frac{1}{2}\right)^3 = \frac{1}{8}$ – about 12.5%. In an alpha decay of uranium-238 ($^{238}_{92}\mathrm{U}$), the daughter has mass number $238 - 4 = 234$ and atomic number $92 - 2 = 90$: thorium-234.

Exam tips

- Photon energy is $E = hf$; below the **threshold frequency** no electrons are emitted **however bright** the light (the photoelectric effect).
- Use $K_{\max} = hf - \phi$ for the fastest photoelectrons (ϕ = work function).
- Electrons jump between **discrete energy levels** by absorbing/emitting a photon whose energy equals the level gap — the source of line spectra.
- In fission and fusion the small **mass lost** becomes energy via $E = mc^2$.
- Balance decay equations by conserving **mass number, charge, and lepton number** (write the antineutrino in β^-, the neutrino in β^+), and halve the sample every **half-life** ($(\frac{1}{2})^n$ after n half-lives).