Quantum physics

A-Level Physics

Photons: the particle nature of light

Electromagnetic radiation behaves like **particles** as well as like a wave. The particles of EM radiation are **photons** 光子—small packets (”**quanta**” 量子) of EM energy that travel at the speed of light.

Energy of a photon

A photon of **frequency** 频率 f has energy

$$E = hf,$$

where $h = 6.63 \times 10^{-34}$ J s is the **Planck constant** 普朗克常量. Using $c = f\lambda$:

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

Higher-frequency (shorter-**wavelength** 波长) photons carry more energy: one γ-ray photon carries far more than one radio photon.

The electronvolt

The **electronvolt** 电子伏特 (eV) is a handy energy unit on the atomic scale:

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

It is the **kinetic energy** 动能 an **electron** 电子 gains moving through a **potential difference** 电势差 of 1 V. For example, a visible photon ($\lambda \approx 500$ nm) has energy ≈ 2.5 eV. To go eV → J multiply by 1.60×10^{-19}; J → eV divide.

Momentum of a photon

A photon also carries **momentum** 动量:

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

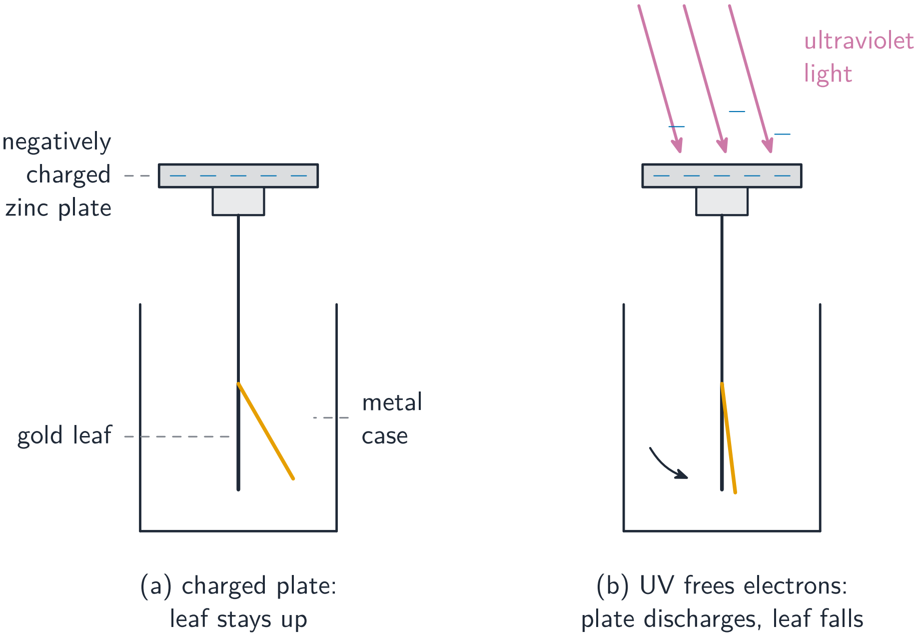
It has zero rest mass but a non-zero momentum E/c. Radiation pressure (photons pushing on a surface) follows from this.

Photoelectric effect

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

Image: Grendelkhan, CC BY-SA 4.0 (commons.wikimedia.org)

When EM radiation of high enough frequency hits a metal, **electrons are emitted**. These are **photoelectrons** 光电子, and the effect is the **photoelectric effect** 光电效应.



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

Threshold frequency and work function

Each metal has a lowest photon frequency, the **threshold frequency** 极限频率 f_0, below which **no** electrons come out, however bright the light. The **work function** 逸出功 Φ is the **least energy** needed to free an electron from the surface:

$$\Phi = hf_0.$$

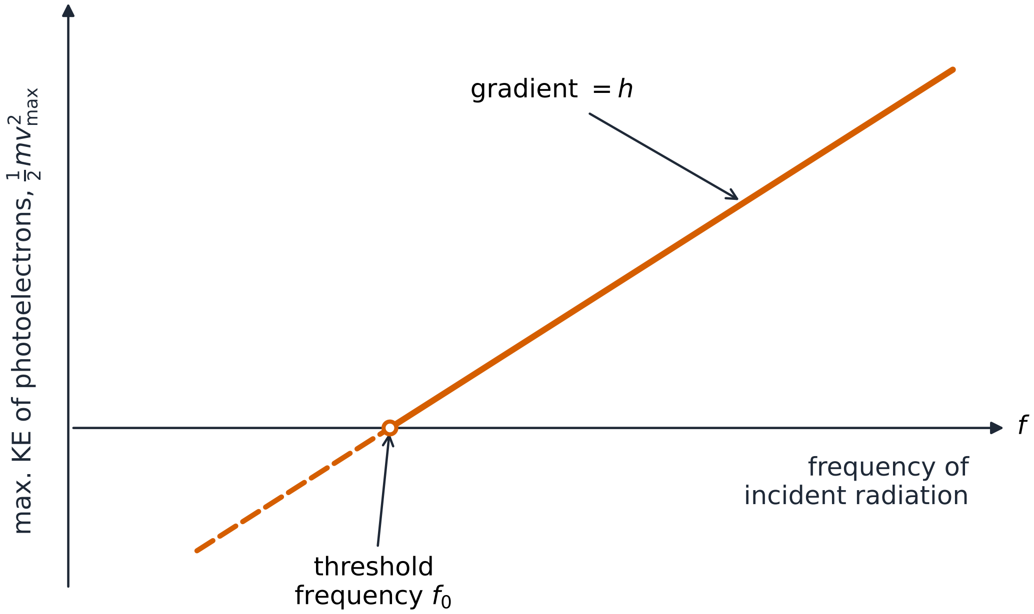
Different metals have different work functions (about 2–5 eV).

Einstein's photoelectric equation

One photon gives all its energy to one electron. If the photon energy hf is more than the work function, the electron escapes with kinetic energy up to a maximum:

$$hf = \Phi + \tfrac{1}{2}mv_{\max}^2, \qquad \text{so} \qquad \tfrac{1}{2}mv_{\max}^2 = h(f - f_0).$$

So the maximum KE of photoelectrons depends **linearly on frequency**, not on brightness.



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

Why the wave model fails

A wave model predicts that brightness should set the electrons' kinetic energy, and that emission should happen at any frequency given enough time. But experiments show:

- **no emission below the threshold frequency**, however bright.
- **immediate emission** at or above the threshold, even when dim.
- **maximum KE depends on frequency**, not brightness.
- the **number of photoelectrons** (the current) depends on brightness.

The photon model explains this: light arrives as photons each of energy hf. One photon–electron interaction either has enough energy to free the electron ($hf \geq \Phi$) or it does not.

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. with brightness. Doubling the brightness doubles the current but does not change the maximum KE.

Wave–particle duality

The photoelectric effect is strong evidence for the **particle** nature of light. But **interference** 干涉 (Young's double slit, the **diffraction grating** 衍射光栅) and **diffraction** 衍射 show its **wave** nature. So light has **both** wave and particle sides —this is **wave–particle duality** 波粒二象性.

De Broglie hypothesis

If a wave can act like particles, perhaps particles can act like waves. De Broglie proposed that any moving particle has a **de Broglie wavelength** 德布罗意波长:

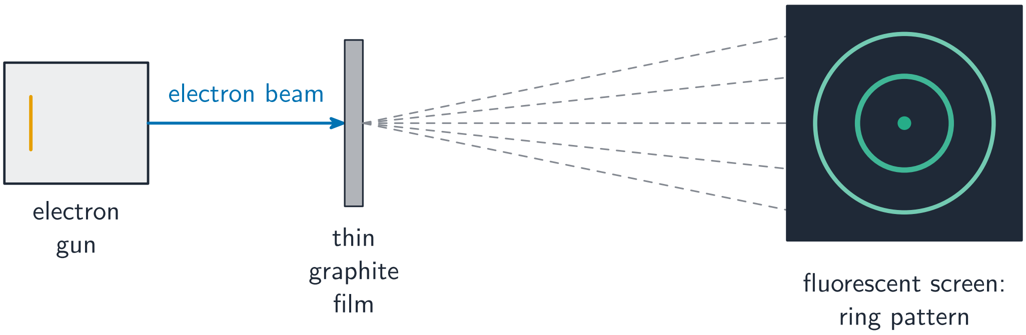
$$\lambda = \frac{h}{p},$$

where $p = mv$. Example: an electron at $v = 4.9\times10^{7}$ m s^{-1} has $p = 4.46\times10^{-23}$ kg m s^{-1}, so $\lambda = 1.49 \times 10^{-11}$ m ≈ 0.015 nm —close to atomic spacings.

Electron diffraction

When electrons are fired at a **crystal lattice** 晶格 (e.g. thin graphite), they make a **diffraction pattern** of bright rings on a screen —exactly what waves of wavelength $\lambda = h/p$ would do. This is direct evidence for the **wave nature of particles** (**electron diffraction** 电子衍射): only waves diffract, yet electrons do.

A faster electron has more momentum, so a **shorter** de Broglie wavelength, which diffracts less —the rings move **closer together**. Slowing the electrons spreads the rings apart. To calculate: $p = \sqrt{2mE_{\mathrm{K}}}$, and for an electron accelerated through p.d. V, $E_{\mathrm{K}} = eV$, so $\lambda = h/\sqrt{2m_e eV}$.

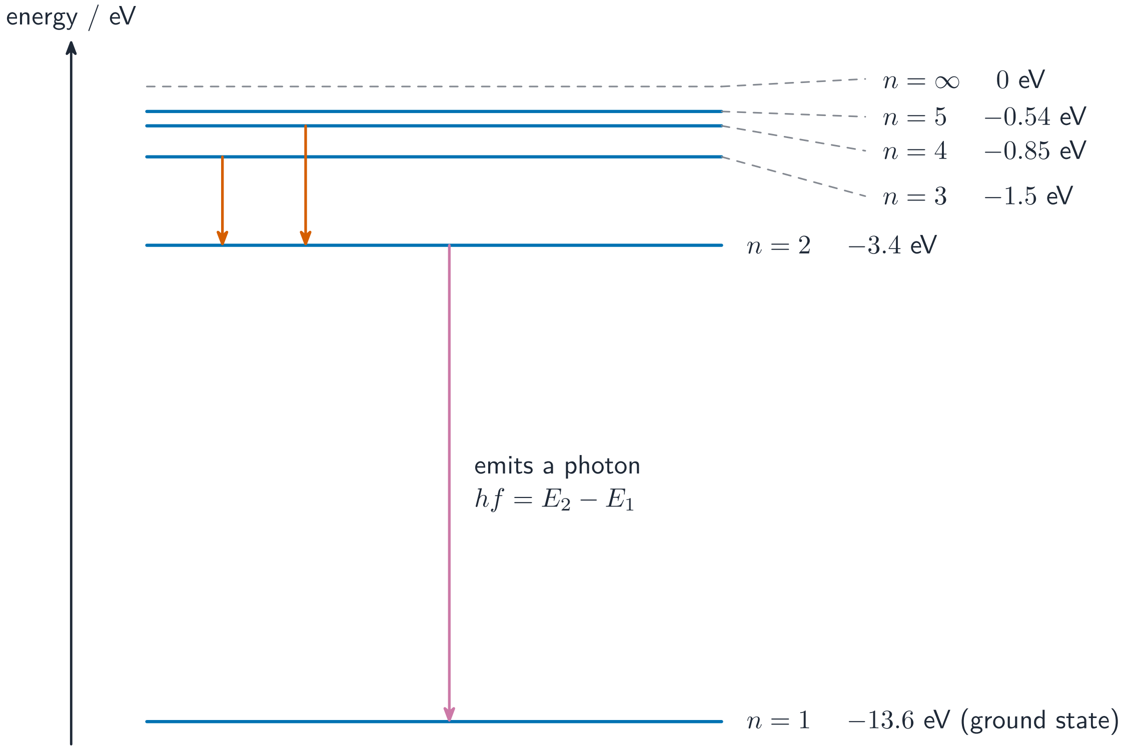


Electrons fired at graphite form a ring diffraction pattern —only waves diffract, so electrons behave as waves

Energy levels in atoms

In an isolated atom, electrons can only sit at certain **discrete 分立 energy levels 能级**—never in between. The lowest is the **ground state 基态**; the others are **excited states 激发态**.

By convention, energies are written **negative**, with $E = 0$ for an electron just free of the atom. For hydrogen the ground state is $E_1 = -13.6$ eV; higher states approach zero.



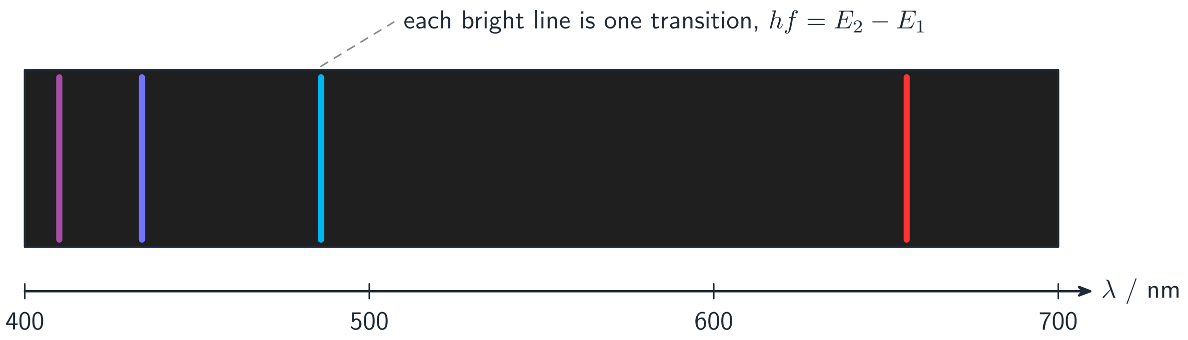
The electron energy levels of hydrogen are discrete and negative, with the ground state at -13.6 *eV*

Emission spectrum

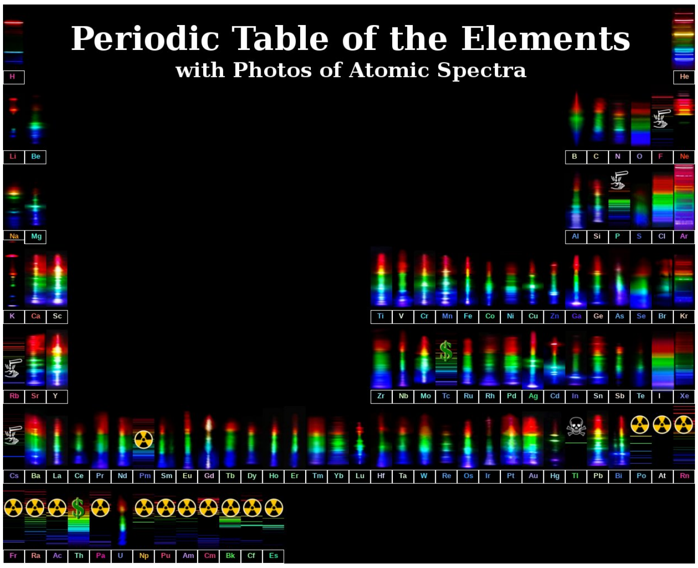
When an electron drops from a higher level E_2 to a lower level E_1, it emits one photon of energy

$$hf = E_2 - E_1.$$

(Both energies are negative; their difference is positive.) Because the levels are discrete, only certain photon energies —and so certain wavelengths —come out. The **emission spectrum 发射光谱** is a set of **sharp bright lines** on a dark background, one line per **transition 跃迁**. The pattern is a ”fingerprint” of the element.



The emission spectrum of hydrogen is a set of sharp bright lines on a dark background

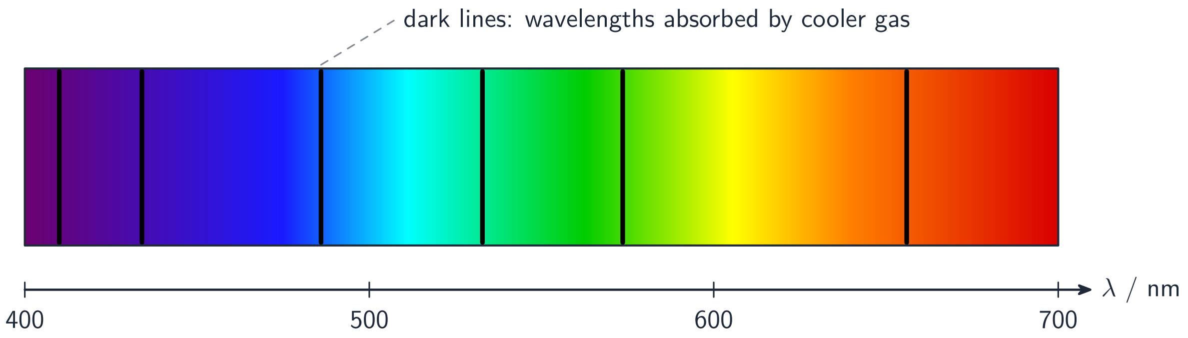


Real emission spectra of the elements: each one is a unique set of bright lines – a fingerprint of that element

Image: Umop503, CC0 (commons.wikimedia.org)

Absorption spectrum

When white light passes through a cool gas, photons whose energy exactly matches an upward transition are absorbed. The light then shows **dark lines on a bright background** —the **absorption spectrum** 吸收光谱. The dark lines sit at the **same wavelengths** as the emission lines of the same gas.



Dark absorption lines in the Sun's spectrum mark the wavelengths absorbed by cooler gas

Calculations

For a transition between two known levels:

$$hf = E_2 - E_1, \qquad \lambda = \frac{hc}{E_2 - E_1}.$$

Work in consistent units —convert eV to joules ($\times\ 1.60 \times 10^{-19}$) before finding λ in metres, or use $hc \approx 1240$ eV nm for a quick estimate.