

Photon energy, work function and matter waves

Physics grades 11-12 (A Level · IB · Class 11-12) · Lesson

Quick answer: Light comes in photons of energy $E = hf$. In the photoelectric effect a photon ejects an electron only if hf is at least the work function ϕ , and the electron then has maximum kinetic energy $K_{\max} = hf - \phi$. Particles also show wave behaviour, with de Broglie wavelength $\lambda = h/p$.

Level: Physics grades 11-12 (A Level · IB · Class 11-12) · **Curriculum:** IB E.2

What is a photon?

Light travels as a wave, yet it is absorbed and emitted in tiny packets. Each packet is a photon, and its energy depends only on the frequency of the light, not on how bright the beam is. Violet photons carry more energy than red ones, and X-ray photons far more.

Formula

$$E = hf = hc / \lambda$$

E = photon energy (J), h = Planck constant = 6.63×10^{-34} J s, f = frequency (Hz), $c = 3.00 \times 10^8$ m/s, λ = wavelength (m). Use $1 \text{ eV} = 1.60 \times 10^{-19}$ J to convert to electronvolts.

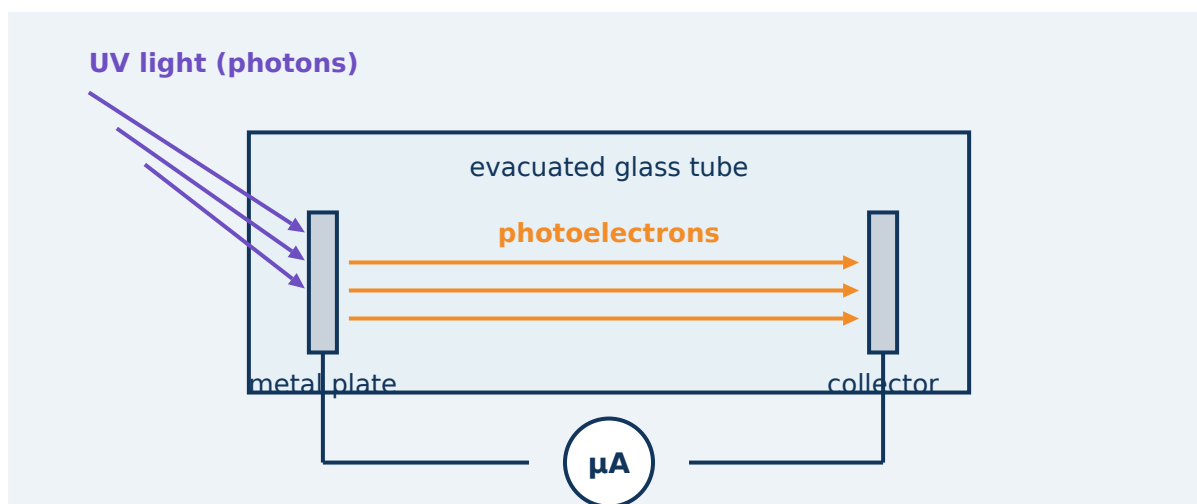
Worked example

Calculate the energy of a photon of wavelength 450 nm.

$$E = hc/\lambda = (6.63 \times 10^{-34} \times 3.00 \times 10^8) / (450 \times 10^{-9}) = \mathbf{4.42 \times 10^{-19} \text{ J}} = 4.42 \times 10^{-19} / 1.60 \times 10^{-19} = \mathbf{2.76 \text{ eV}}.$$

What is the photoelectric effect?

When light of high enough frequency shines on a clean metal surface, electrons are ejected. A negatively charged zinc plate loses its charge in ultraviolet light, but a bright red lamp has no effect at all. This puzzled physicists because the wave model predicted that any bright light should eventually work.



Photons strike the plate and eject electrons. The microammeter records the flow of photoelectrons to the collector.

Definition

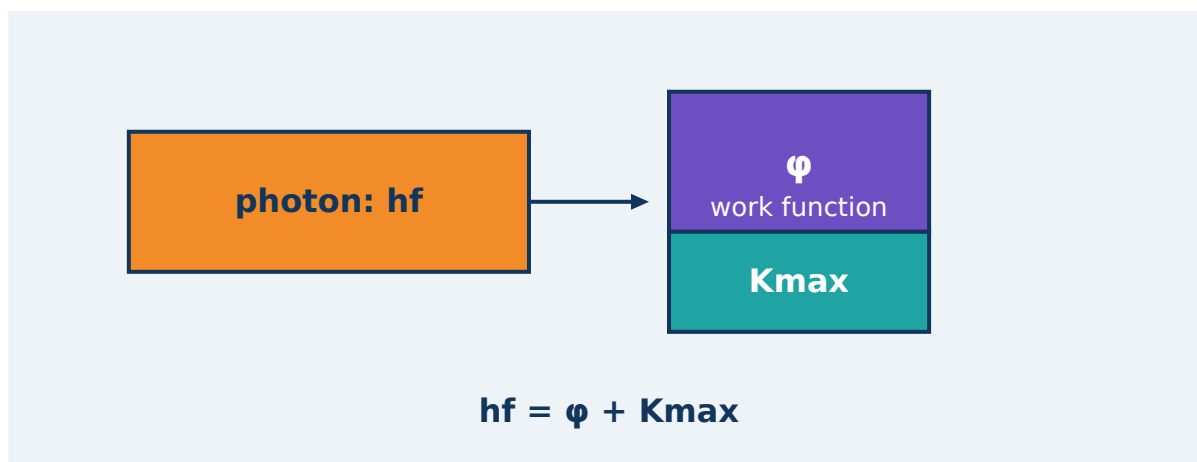
The **work function** ϕ is the minimum energy needed to remove an electron from the surface of a metal. The **threshold frequency** f_0 is the lowest frequency that can eject electrons: $\phi = hf_0$.

How does Einstein's equation explain the observations?

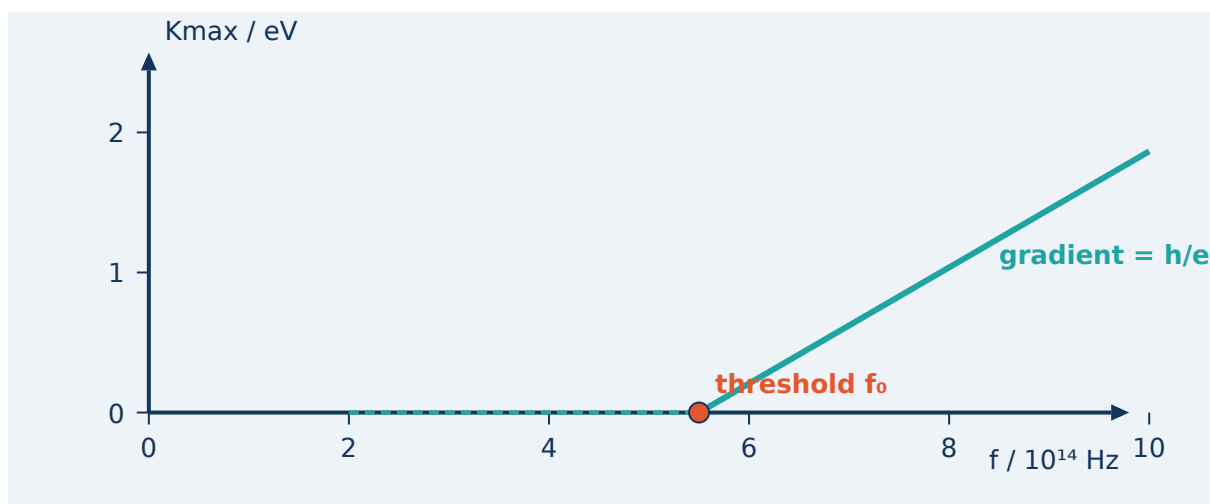
Einstein proposed that one photon gives all its energy to one electron. Part pays for escaping the metal and the remainder becomes kinetic energy. The most energetic electrons come from the surface and have the maximum kinetic energy.

Key law

$hf = \phi + K_{\max}$, so $K_{\max} = hf - \phi$. The stopping potential V_s is the reverse voltage that just stops the fastest electrons: $eV_s = K_{\max}$.



Energy conservation for one photon and one electron: the work function is the minimum energy needed to escape the metal.



Worked example

Sodium has a work function of 2.30 eV. Light of wavelength 400 nm falls on it. Calculate $K_{\max}$ and the stopping potential.

$$E = hc/\lambda = 4.97 \times 10^{-19} \text{ J} = 3.11 \text{ eV}. K_{\max} = 3.11 - 2.30 = \mathbf{0.81 \text{ eV}}, \text{ so } V_s = \mathbf{0.81 \text{ V}}.$$

Observation	Wave model	Photon model
No emission below f_0 , however bright	predicts emission if bright enough	one photon is too weak, no matter how many
Emission is instant	predicts a delay while energy builds up	one photon gives its energy at once
$K_{\max}$ independent of intensity	predicts larger $K_{\max}$ for brighter light	brightness changes the number of photons, not their energy
Current proportional to intensity	agrees	more photons, more electrons

What does de Broglie's equation say about matter?

If light waves behave like particles, perhaps particles behave like waves. Louis de Broglie suggested that a particle of momentum p has a wavelength, and electron diffraction by crystals confirmed it. This is wave-particle duality.

Formula

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

λ = de Broglie wavelength (m), p = momentum (kg m/s), m = mass (kg), v = speed (m/s).

Worked example

Calculate the de Broglie wavelength of an electron moving at 3.0×10^6 m/s.

$$\lambda = h/(mv) = 6.63 \times 10^{-34} / (9.11 \times 10^{-31} \times 3.0 \times 10^6) = \mathbf{2.4 \times 10^{-10} \text{ m}} \text{ (0.24 nm)}, \text{ similar to the spacing of atoms in a crystal.}$$

Common mistake

Students think brighter light gives faster electrons. A brighter beam gives **more** electrons per second but not faster ones: speed depends on frequency only.

Lina's tip

Always change the photon energy to the same unit as the work function before you subtract. Most work functions are given in eV, so convert hc/λ using $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$.

Key points to remember

- Photon energy: $E = hf = hc/\lambda$, with $h = 6.63 \times 10^{-34} \text{ J s}$.
- Einstein: $hf = \phi + K_{\text{max}}$; threshold frequency $f_0 = \phi/h$.
- Stopping potential: $eV_s = K_{\text{max}}$.
- Intensity changes the number of photoelectrons, not their maximum energy.
- de Broglie: $\lambda = h/p = h/(mv)$.

Photon energy, work function and matter waves: frequently asked questions

What is the work function?

The work function ϕ is the minimum energy needed to free an electron from a metal surface. It is different for every metal and is often quoted in electronvolts.

Why does bright red light not release electrons from zinc?

Each red photon has too little energy to free an electron. Energy is not shared between photons, so more red photons do not help.

What does the gradient of a K_{max} against f graph give?

The gradient equals Planck's constant h , and the intercept on the energy axis is $-\phi$. The frequency axis intercept is the threshold frequency.

What is an electronvolt?

One electronvolt is the energy gained by an electron moving through a potential difference of 1 V, which equals $1.60 \times 10^{-19} \text{ J}$.

How was the wave nature of electrons shown?

Electrons directed at thin crystals produce diffraction patterns like those of waves. The measured wavelength matches $\lambda = h/p$.