

Photons, work functions and matter waves

AP Physics 2 (algebra-based) · Lesson

Quick answer: Light is absorbed and emitted in photons, each carrying energy $E = hf$. In the photoelectric effect one photon frees one electron when its energy exceeds the work function, giving $K_{\max} = hf - \phi$. Moving particles also have a wavelength $\lambda = h / p$, which is why electrons diffract. Light and matter show wave and particle behaviour.

Level: AP Physics 2 (algebra-based) · **Curriculum:** AP P2 Unit 15

What is a photon?

Light travels as a wave, but it also arrives in packets of energy called photons. Each photon of frequency f carries the same fixed energy and cannot be divided. A bright beam contains more photons per second, but a photon of blue light always carries more energy than a photon of red light.

Definition

A **photon** is a quantum of electromagnetic radiation with energy $E = hf$, where h is the Planck constant and f is the frequency of the light.

Formula

$$E = hf = hc / \lambda \quad p = h / \lambda$$

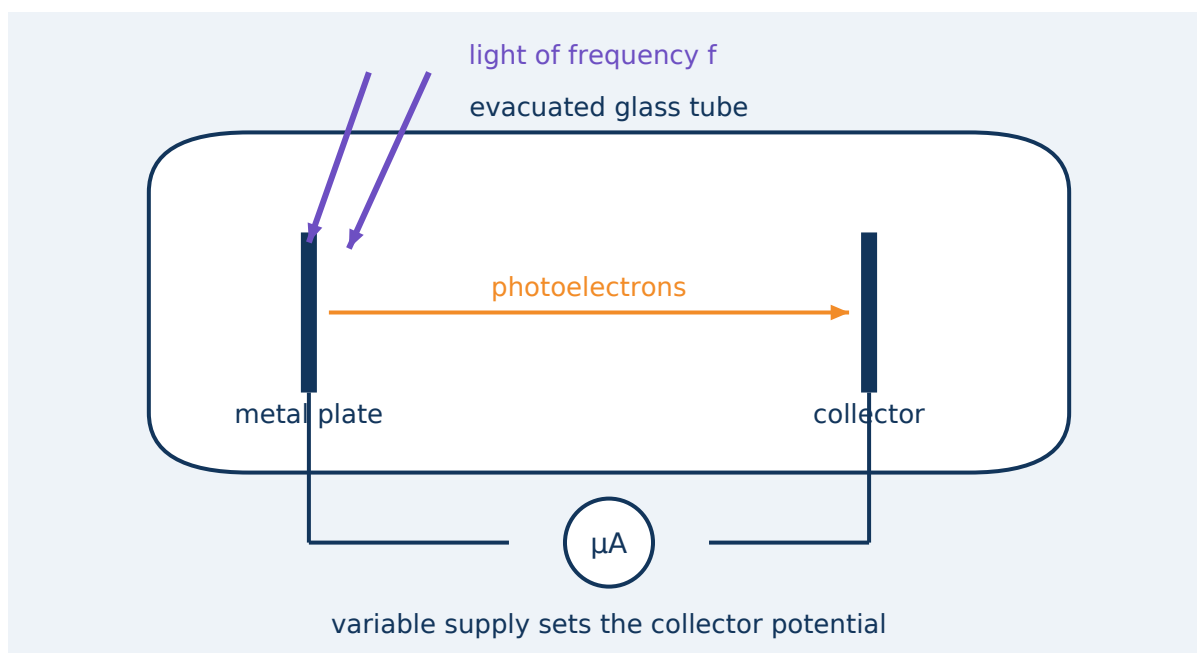
E is the photon energy (J or eV), $h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s} = 4.14 \times 10^{-15} \text{ eV}\cdot\text{s}$, f is the frequency (Hz), $c = 3.00 \times 10^8 \text{ m/s}$, λ is the wavelength (m) and p is the momentum (kg·m/s). A handy value is $hc = 1240 \text{ eV}\cdot\text{nm}$, and $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$.

Worked example

Find the energy of a photon of blue light of wavelength 450 nm. Method: $E = hc / \lambda = 1240 \text{ eV}\cdot\text{nm} / 450 \text{ nm}$. Answer: **2.76 eV**, which is $2.76 \times 1.60 \times 10^{-19} = 4.4 \times 10^{-19} \text{ J}$.

What happens in the photoelectric effect?

When light shines on a clean metal plate, electrons can leave the surface. Experiments show that below a threshold frequency f_0 no electrons escape, however bright the light is. Above f_0 electrons leave at once, and a brighter beam gives more electrons per second without making them faster.

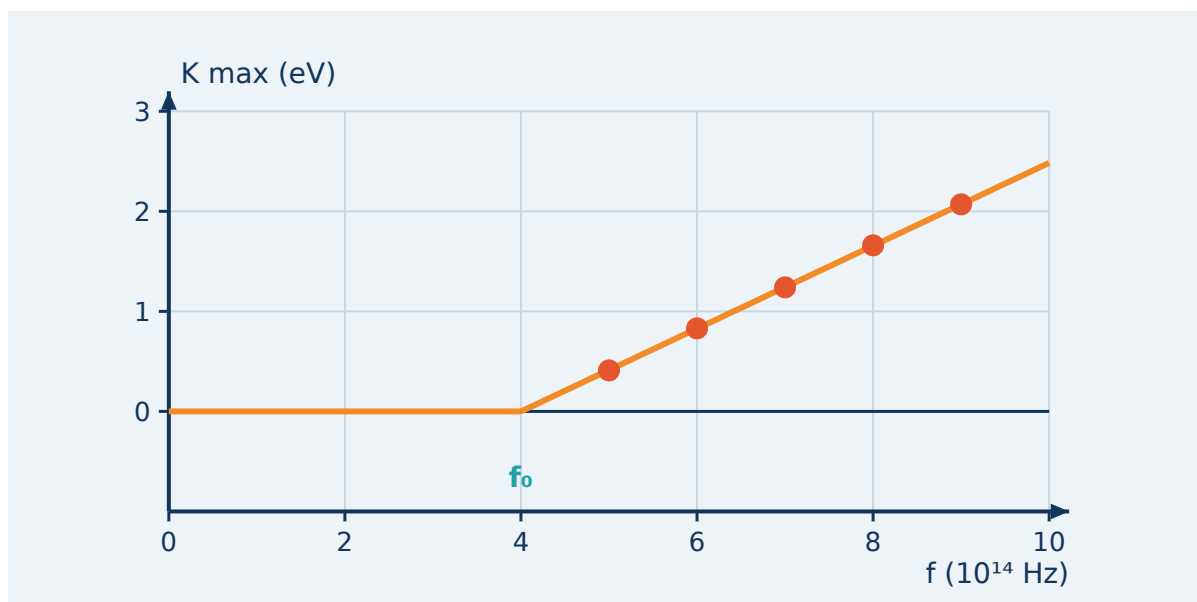


Photoelectric apparatus: the microammeter shows the current of ejected electrons.

The wave model cannot explain this, because a bright wave should give any electron enough energy after a short delay. The photon model can: one photon gives all its energy to one electron in a single event. If the photon energy is less than the work function ϕ , the minimum energy needed to free an electron, nothing happens.

Key law

$K_{\text{max}} = hf - \phi$. Threshold frequency $f_0 = \phi / h$. The stopping potential V_s satisfies $eV_s = K_{\text{max}}$.



Maximum kinetic energy against frequency: the line starts at the threshold frequency f_0 .

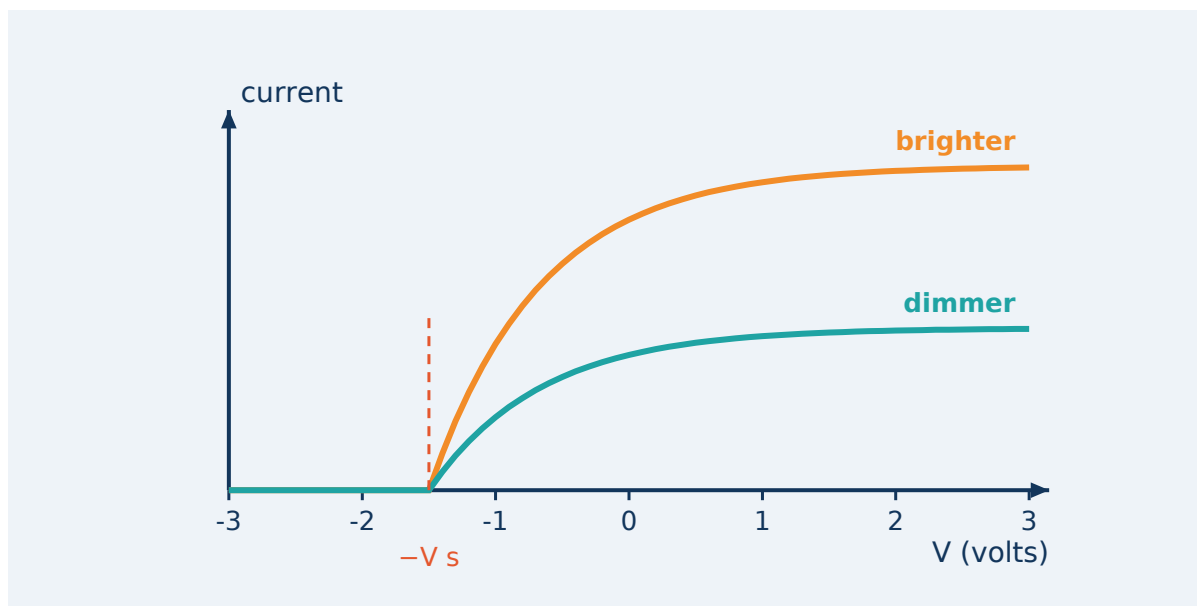
The graph of K_{max} against f is a straight line. Its gradient is h , its horizontal intercept is f_0 and its vertical intercept, extended backwards, is $-\phi$.

Worked example

Sodium has a work function of 2.28 eV. Ultraviolet light of wavelength 400 nm falls on it. Data: $E = 1240 / 400 = 3.10$ eV. Method: $K_{\text{max}} = 3.10 - 2.28$. Answer: **0.82 eV**, so the stopping potential is 0.82 V. The threshold wavelength is $1240 / 2.28 = 544$ nm.

Common mistake

Brighter light does *not* raise K_{max} . Intensity changes the number of photons, so it changes the current. Only the frequency changes K_{max} and the stopping potential.



Current against potential: both curves reach zero at the same stopping potential.

What is the de Broglie wavelength?

Matter also behaves like a wave. A particle of momentum p has a wavelength $\lambda = h / p$. For everyday objects the wavelength is far too small to notice. For an electron it is about the size of an atom, so electrons diffract through crystals and make interference patterns just like light.

Evidence	Which model it supports	Why
Photoelectric effect	Particle (photon)	Energy arrives in packets; threshold frequency
Double-slit fringes	Wave	Interference needs overlapping waves
Electron diffraction	Wave nature of matter	Electrons make fringes in crystals
Single photons build fringes	Both	Each arrives at one spot, yet the pattern is a wave

Worked example

An electron is accelerated through 150 V. Its kinetic energy is $150 \text{ eV} = 2.40 \times 10^{-17} \text{ J}$.

Method: $p = \sqrt{(2mK)} = \sqrt{(2 \times 9.11 \times 10^{-31} \times 2.40 \times 10^{-17})} = 6.61 \times 10^{-24} \text{ kg}\cdot\text{m/s}$, then $\lambda =$

h / p . Answer: $1.00 \times 10^{-10} \text{ m}$, about the spacing of atoms in a crystal.

Lina's tip

Keep two bins in your head: how *many* photons (intensity, current) and how *energetic* each photon is (frequency, K max). Every photoelectric question is a question about one of the two bins.

Key points to remember

- Photon energy: $E = hf = hc / \lambda$, with $hc = 1240 \text{ eV}\cdot\text{nm}$.
- Photoelectric effect: $K_{\text{max}} = hf - \phi$, and $\text{eV s} = K_{\text{max}}$.
- No electrons below the threshold frequency $f_0 = \phi / h$, however bright the light.
- Intensity sets the current; frequency sets K max and the stopping potential.
- de Broglie wavelength: $\lambda = h / p$; electrons diffract through crystals.

Photons, work functions and matter waves: frequently asked questions

What is the work function of a metal?

The work function ϕ is the minimum energy needed to remove an electron from the surface of the metal. A photon with less energy than ϕ cannot free an electron, however many photons arrive.

Why does brighter light not increase the maximum kinetic energy of photoelectrons?

Brighter light means more photons per second, but each photon still has the same energy hf . Each electron receives its energy from one photon, so K max is unchanged while the current rises.

How do you find Planck constant from a photoelectric graph?

Plot K max (or eV s) against frequency. The gradient of the straight line equals h . The intercept on the frequency axis gives the threshold frequency, and the vertical intercept is minus the work function.

What does the de Broglie wavelength tell us?

It tells us the wavelength of a moving particle, $\lambda = h / p$. If this wavelength is comparable to the size of an opening or atomic spacing, wave effects such as diffraction become visible.

Why can a person not be diffracted like an electron?

A person has a very large momentum, so the de Broglie wavelength is about 10^{-35} m . No door or gap is small enough to make wave effects noticeable, so we see only particle-like motion.