Quantum physics

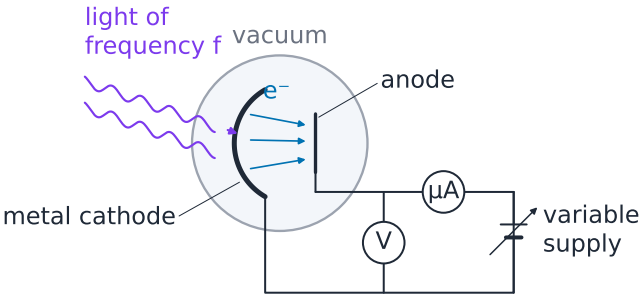
E.2 · AHL

A dim UV lamp beats a bright red one

> Light delivers its energy in packets of hf.

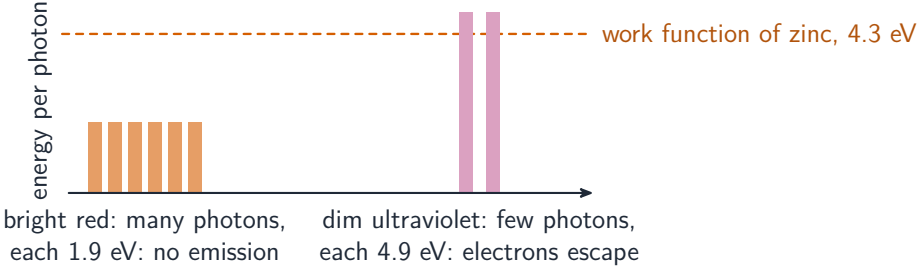
- Suitable UV can discharge a clean negative zinc plate.
- Ordinary red illumination is below the single-photon threshold; brightness still affects allowed emission rate.
- Photons $\rightarrow$ matter waves $\rightarrow$ duality $\rightarrow$ Compton.

The photoelectric effect



- Single-photon emission needs photon energy at least the **work function**.
- There is no long accumulation delay; saturation current scales with photon rate under fixed conditions.

Bright red light frees no electrons



One photon frees one electron: brightness cannot add them up

Where the wave theory fails

Wave theory predicts

Any frequency works if bright enough.

A delay for dim light; brighter means faster electrons.

Experiments show

A **threshold frequency**.

No delay; $E_{\max}$ depends only on frequency.

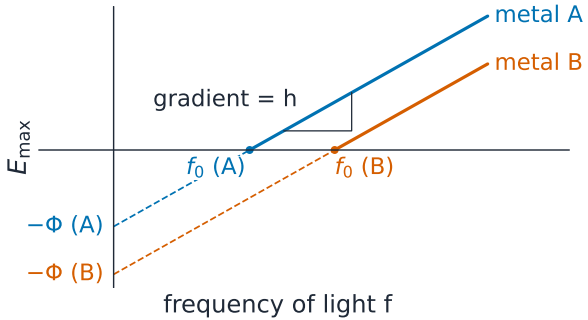
Einstein's equation

- One photon gives all its energy to one electron.
- Zinc, 4.3 eV, with 200 nm ultraviolet (6.2 eV) gives 1.9 eV.

$$E_{\max} = hf - \Phi$$

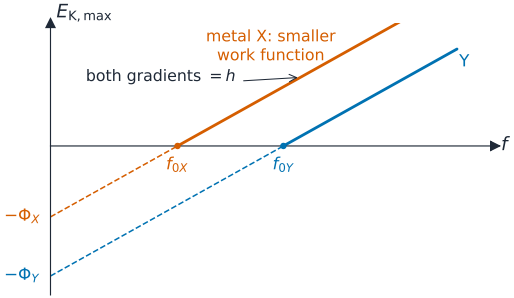
Threshold when $hf_0 = \Phi$.

Reading the graph



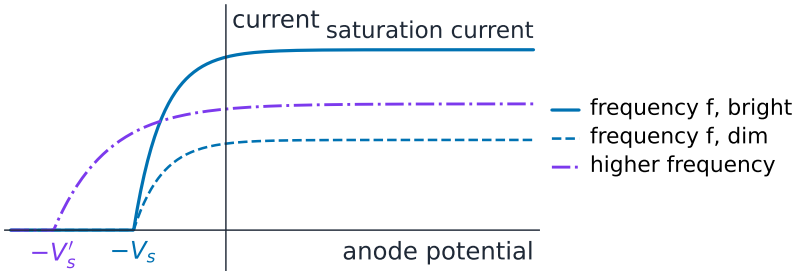
- Gradient h for every metal; intercept f_0.
- Extended back, the line meets the energy axis at $-\Phi$.

$E_{k,\max}$ against frequency



Extended back, each meets the energy axis at $-\Phi$

Stopping potential



- $eV_s = E_{\max}$; a V_s against f graph has gradient h/e.
- Intensity changes the current, frequency changes V_s.

Check: brighter light

Your turn

Above threshold in the single-photon regime, intensity doubles at fixed frequency, surface efficiency and complete collection. What happens to saturation current and stopping potential?

A. Current doubles, stopping potential doubles
B. Current doubles, stopping potential unchanged
C. Current unchanged, stopping potential doubles
D. Both unchanged

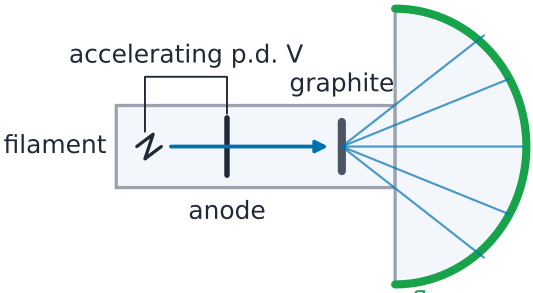
The de Broglie wavelength

- An electron through 100 V has $\lambda = 1.2 \times 10^{-10}$ m, an atom's width.
- A tennis ball has $\lambda \approx 10^{-34}$ m, far too small to notice.

$$\lambda = \frac{h}{p} \qquad p = \sqrt{2 m_e e V}$$

The momentum substitution is for non-relativistic electrons accelerated from rest through voltage magnitude V.

Electron diffraction

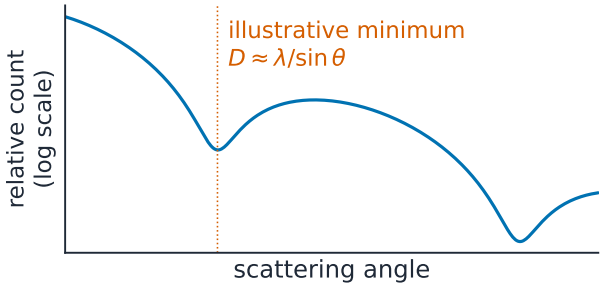




rings on the screen

- Rings form because electrons diffract like waves.
- Higher voltage, shorter wavelength, smaller rings.

Sizing a nucleus with electrons



- Use the stated approximate model D $\approx \lambda/\sin\theta$, not a universal exact nuclear formula.
- 3.0×10^{-15} m at 35° gives $D = 5.2 \times 10^{-15}$ m.

Wave–particle duality

Light

Wave: diffraction, interference.

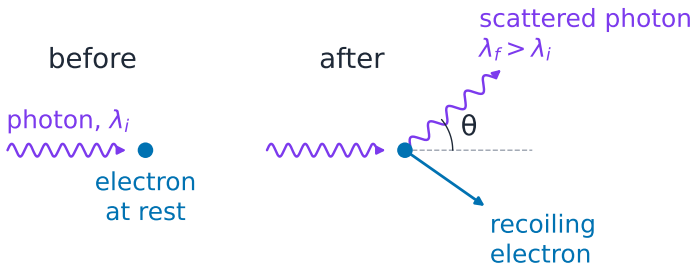
Particle: **photoelectric effect**, Compton.

Electrons

Wave: electron diffraction.

Particle: charge, mass, single dots.

Compton scattering



- The photon gives energy and momentum to the electron.
- For a nonzero photon deflection from a resting free electron, the outgoing wavelength is longer.

The Compton shift

- $h/m_e c = 2.43 \times 10^{-12}$ m; largest shift at 180°.
- Photons carry momentum h/λ: strong evidence for particles.

$$\Delta\lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

Initially resting free-electron model; θ is the photon deflection angle.

Check: a scattered X-ray

Your turn

Photons of wavelength 7.10×10^{-11} m scatter through 90° from initially resting free electrons. Use $h/(m_e c) = 2.43 \times 10^{-12}$ m. What is the outgoing wavelength?

A. 6.86×10^{-11} m

B. 7.10×10^{-11} m

C. 7.34×10^{-11} m

D. 7.59×10^{-11} m

Exam tips

> The elementary photoelectric model assumes one-photon absorption; Compton also tests momentum transfer.

- Intensity sets the current; frequency sets $E_{\max}$.
- For an accelerated electron find p first, then $\lambda = h/p$.
- The Compton shift depends only on the angle.

Check yourself

Try these

HL. Find threshold wavelength for an assigned sodium-surface $\Phi = 2.3$ eV. Use $h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^{8}$ m/s and 1 eV $= 1.60 \times 10^{-19}$ J.

HL. Find an electron's de Broglie wavelength after acceleration from rest through 150 V in the classical model; use $m_e = 9.11 \times 10^{-31}$ kg and the constants above.

HL. Explain why Compton scattering is strong evidence for photons.