Unit 21 · Photons

STUDY NOTES

WHAT NEB'S GRADE 12 EXAM ASKS

- **CDC's grid (2078):** Modern Physics (Units 20–25 together): 19 of 75 marks
- **The paper:** 11 MCQs × 1 · 8 short × 5 · 3 long × 8; 3 hours; 1 mark per expected point
- **CDC's model paper:** short (5): ultraviolet of 1.5×10^{15} Hz on aluminium, $\varphi = 6.6 \times 10^{-19}$ J: show $v_{max} = 8.6 \times 10^5$ m/s; brighter ultraviolet: v_{max} **unchanged** (each photon still hf; only more electrons)
- **MCQ (1 mark)**
  - E_k in Einstein's equation: maximum KE
  - photoelectric emission
  - same intensity, which radiation: ultraviolet
  - a photon is a quantum
  - more current: more intensity
  - V_0 from φ and E
  - f_0 from φ
  - light $4f_0$: KE $3hf_0$
- **Short and long (5 or 8 marks, in parts)**
  - define threshold frequency, stopping potential, work function, photon
  - threshold frequency as evidence for quanta; two other particle-like observations
  - derive Einstein's equation; explain the laws from it
  - Millikan's experiment for h: the graph, slope, intercepts
  - f_0, photon energy, KE, V_0, λ_0; will 436 nm free electrons from a metal?
  - graph of E_k against f: f_0, h; a metal of lower φ; why a range of KE
  - photosynthesis not with infrared; two uses

Key terms

Quantum: a packet of radiant energy hf; radiation is given out and taken in only as $hf, 2hf, \ldots$ (Planck, 1900).

Photon: a packet of electromagnetic radiation travelling at c (Einstein, 1905); no rest mass.

Photoelectric effect: ejection of electrons from a metal surface when light of high enough frequency falls on it.

Photoelectrons: the electrons ejected; their current is the **photoelectric current**.

Stopping (cut-off) potential V_0: the least retarding potential that stops even the fastest photoelectrons.

Saturation current: the greatest current, when every electron emitted is collected.

Work function φ: least energy to free an electron from a metal's surface.

Threshold frequency f_0: least frequency that ejects electrons, ϕ/h.

Threshold wavelength λ_0: longest wavelength that ejects electrons, hc/ϕ.

Electronvolt: energy gained by an electron through 1 V, 1.6×10^{-19} J.

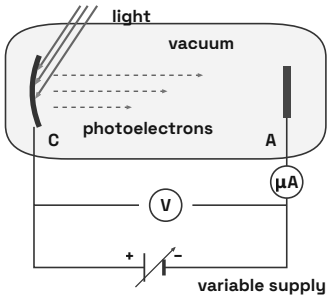
Formulas

$E = hf = \dfrac{hc}{\lambda}$	$h = 6.63 \times 10^{-34}$ J s **Use:** photon energy; eV $\approx 1240/\lambda$(nm)
$p = \dfrac{E}{c} = \dfrac{h}{\lambda}$	no rest mass **Use:** photon momentum
$eV_0 = \frac{1}{2}mv_{max}^2$	stopping potential **Use:** fastest electrons
$hf = \phi + \frac{1}{2}mv_{max}^2$	one photon, one electron **Use:** Einstein's equation
$\phi = hf_0 = \dfrac{hc}{\lambda_0}$	threshold **Use:** work function
$\frac{1}{2}mv_{max}^2 = hc\left(\dfrac{1}{\lambda} - \dfrac{1}{\lambda_0}\right)$	from wavelengths **Use:** max KE
$V_0 = \dfrac{h}{e}f - \dfrac{\phi}{e}$	slope h/e **Use:** Millikan's line

Quantum theory

- **blackbody radiation** didn't fit wave theory; **Planck** (1900): energy given out and absorbed in packets $E = hf$; h Planck's constant
- energy as hf, $2hf$, $3hf$, never $1.5hf$ (like charge in units of e)
- also explained: specific heats at low temperature, photoelectric effect, Compton effect, hydrogen's spectral lines, X-ray spectra → **quantum mechanics** (1920s)
- **Einstein** (1905): light also **travels** as packets, **photons**
- photon: energy hf, speed c, **no rest mass**, momentum h/λ, no charge; a beam's intensity = photons per second × hf

Photoelectric effect

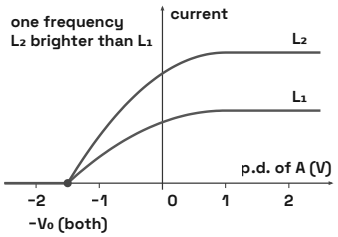


Photocell: light on emitter C frees electrons; collector A; microammeter; a variable p.d. makes A positive or negative.

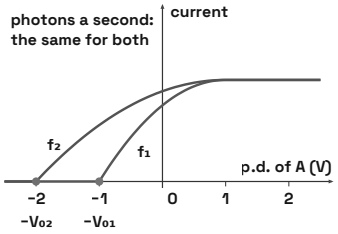
- Hertz (1887): ultraviolet helps sparks jump; Hallwachs, Lenard: light frees **electrons**
- A positive: electrons collected → current; **saturation** once all collected
- A negative (**retarding**): only fast electrons arrive; at V_0, none: $eV_0 = \frac{1}{2}mv^2_{\max}$

Laws of photoelectric emission

1. **threshold frequency** f_0, different for each metal; below it no emission, however bright
2. **no delay** (under 10^{-9} s), even in dim light
3. **max KE rises with frequency**, not with brightness
4. **number of electrons** (saturation current) ∝ intensity



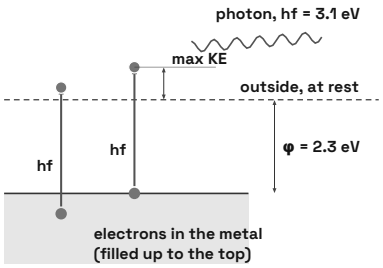
Current against p.d. for one frequency at two intensities: different saturation currents, the same stopping potential V_0.



Current against p.d. at two frequencies: the higher frequency needs a larger stopping potential.

- same **intensity**, higher frequency → **fewer** photons (each carries more) → saturation current **lower**
- why waves fail: brighter wave should give faster electrons; any frequency should work in time; dim light should delay
- ejected electrons have a **range** of KE: those from deeper lose energy on the way out; $hf - \phi$ is the **maximum**

Einstein's photoelectric equation



A photon's energy hf: φ to free the electron at the surface, the rest its kinetic energy.

1. light comes as photons, each hf
2. least energy to leave the surface: φ
3. one photon gives **all** its energy to **one** electron
4. energy left as KE: $\frac{1}{2}mv^2_{\max} = hf - \phi \rightarrow hf = \phi + \frac{1}{2}mv^2_{\max}$
5. at f_0, KE = 0: $\phi = hf_0 \rightarrow \frac{1}{2}mv^2_{\max} = h(f - f_0)$

Laws explained

- threshold: KE > 0 only if $hf > \phi$; one photon per electron, so no adding up

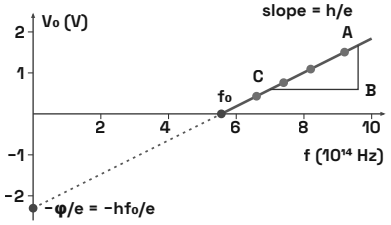
- KE rises in a straight line with f
- brighter: more photons → more electrons, each the same max KE
- no delay: energy handed over at once
- $E < \phi$: no effect; $E = \phi$: just freed; $E > \phi$: KE up to $E - \phi$
- $\lambda > \lambda_0$: no effect
- alkali metals (Cs … Li): low φ, visible light works; Cu, Ag, Pt need ultraviolet
- work function ≠ ionization energy (free atom); φ is for a solid's free electrons

Model paper's numbers

1. $hf = 6.63 \times 10^{-34} \times 1.5 \times 10^{15} = 9.95 \times 10^{-19}$ J
2. KE $= 9.95 - 6.6 = 3.35 \times 10^{-19}$ J
3. $v = \sqrt{2 \times 3.35 \times 10^{-19} / 9.1 \times 10^{-31}} = 8.6 \times 10^{5}$ m/s

- e.g. φ 0.6 eV, photon 2 eV → $V_0 = 1.4$ V; φ 2.51 eV → $f_0 = 6.08 \times 10^{14}$ Hz; $4f_0$ → KE $3hf_0$
- photosynthesis: infrared photons have too little energy each to drive the reaction, however much arrives

Millikan's verification (1914–16)



Stopping potential against frequency: straight parallel lines for different metals, slope h/e, cutting the frequency axis at f_0.

- clean metal surfaces cut in a vacuum (tarnish changes φ); measure V_0 for several frequencies
- $hf = hf_0 + eV_0 \rightarrow V_0 = (h/e)f - \phi/e$: a straight line
- **slope** h/e (same for every metal) → $h = e \times$ slope
- cuts the **frequency** axis at $f_0 \rightarrow \phi = hf_0$; the V_0 axis (extended) at $-\phi/e$
- lower φ: parallel line, to the left
- E_k against f: slope h, cuts the f axis at f_0

Uses: photocells (automatic doors, burglar alarms, old film sound tracks), photomultipliers, night vision; solar cells, camera sensors and light meters by the **inner** effect (electrons freed inside a semiconductor)

COMMON MISTAKES

✗ f_0 where the line cuts the V_0 axis
✓ where it cuts the **frequency** axis; the V_0 intercept is $-\phi/e$.

✗ work function = ionization energy
✓ ionization is from a free atom; φ from a solid metal.

✗ same intensity, higher frequency, more photons
✓ **fewer** photons, each with more energy.

✗ brighter light, faster electrons
✓ same max KE; **more** electrons.

✗ dim light: emission after a delay
✓ **no delay**.

✗ the photon has a rest mass
✓ none; momentum h/λ.