

Exercise walk-through

22.2

Photoelectric effect

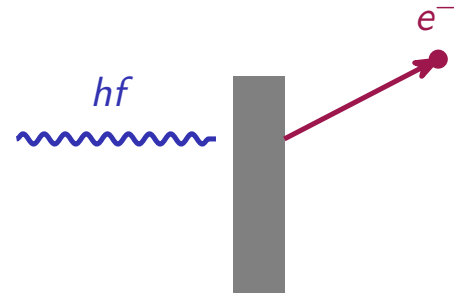
A-Level Physics

One photon frees one electron

EM radiation of high enough frequency hitting a metal emits **photoelectrons**.

$$hf = \Phi + \frac{1}{2}mv_{\text{max}}^2$$

Work function $\Phi = hf_0$ is the least energy to free an electron. Below the **threshold frequency** f_0 , **no** electrons come out, however bright.



Worked example – maximum KE

Work function 2.0 eV; photons of 3.5 eV

$$\begin{aligned}\frac{1}{2}mv_{\text{max}}^2 &= hf - \Phi = 3.5 - 2.0 \\ &= 1.5 \text{ eV}\end{aligned}$$

Maximum KE depends **linearly on frequency**,
not on brightness.

Convert Φ to joules before
subtracting if hf is in joules.
A negative answer means you
are below threshold.

Why the wave model fails

A wave model says brightness should set the KE, and any frequency should work given enough time. Experiment says otherwise:

no emission below f_0 , however bright

immediate emission at or above f_0 , even when dim

max KE depends on frequency, not brightness

the *number* of photoelectrons (the current) depends on brightness

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.

Brighter means more photons, not more energetic ones

A brighter beam of the **same frequency** has more photons per second, each still carrying hf . Doubling the brightness doubles the current but does **not** change the maximum KE.

Exercises 2.1-2.3

2.1 Define **threshold frequency**.

[1]

2.2 Define the **work function** of a metal.

[1]

2.3 Write the **photoelectric equation**.

[1]

Exercises 2.1-2.3

2.1 Define **threshold frequency**.

[1]

2.1

- the **lowest frequency** of radiation that will release electrons from the metal
-

2.2 Define the **work function** of a metal.

[1]

2.2

- the **minimum energy** needed to free an electron from the surface
-

2.3 Write the **photoelectric equation**.

[1]

2.3

- $hf = \Phi + \frac{1}{2}mv_{\max}^2$

Exercises 2.4·3.1

2.4 State why **no** electrons are emitted below the threshold frequency.

[1]

3.1 Below the threshold frequency, increasing the **intensity** of the light:

[1]

☐

A emits more electrons

B emits faster electrons

C emits no electrons

D lowers the threshold frequency

Exercises 2.4·3.1

2.4 State why **no** electrons are emitted below the threshold frequency. [1]

2.4

- each photon has energy $hf < \Phi$, so it **cannot supply** enough energy to free an electron (and energy is one-photon-per-electron)

3.1 Below the threshold frequency, increasing the **intensity** of the light: [1]

☐

A emits more electrons

B emits faster electrons

C emits no electrons

D lowers the threshold frequency

3.1 C

- below threshold, **no electrons** are emitted

Exercises 3.2-3.3

3.2 A metal has a work function of 2.0 eV. Photons of energy 3.5 eV strike it. Find the **maximum kinetic energy** of the photoelectrons. [2]

3.3 Explain why the **maximum KE** of the photoelectrons is independent of intensity, while the **current** is proportional to intensity. [3]

Exercises 3.2-3.3

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3.2

- $\text{KE}_{\text{max}} = hf - \Phi$

$$\text{KE}_{\text{max}} = hf - \phi = 3.5 \text{ eV} - 2.0 \text{ eV} = \mathbf{1.5 \text{ eV}}$$

3.3 Explain why the **maximum KE** of the photoelectrons is independent of intensity, while the **current** is proportional to intensity. [3]

3.3

- each electron absorbs **one photon**, so its max KE depends only on the **photon energy** (hf), set by frequency
- higher intensity means **more photons per second**
- so more electrons per second – a larger current, but the same energy per electron

Exercise 3.4

3.4 A metal has a work function of 3.2×10^{-19} J. Calculate its **threshold frequency**.^[2]

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3.4

- $f_0 = \Phi/h$

$$f_0 = \frac{\Phi}{h} = \frac{3.2 \times 10^{-19} \text{ J}}{6.63 \times 10^{-34} \text{ J s}} = \mathbf{4.8 \times 10^{14} \text{ Hz}}$$

Exercise 3.5 (a)

3.5 In a photoelectric experiment, the maximum kinetic energy KE_{max} of the photoelectrons is plotted against the frequency f of the incident light, giving a straight line.

(a) The line has gradient $6.6 \times 10^{-34} \text{ J s}$. State the quantity this gradient represents. [1]

Exercise 3.5 (a)

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(a) The line has gradient $6.6 \times 10^{-34} \text{ J s}$. State the quantity this gradient represents. [1]

(a) the **Planck constant** h

Exercise 3.5 (b)

3.5 In a photoelectric experiment, the maximum kinetic energy KE_{max} of the photoelectrons is plotted against the frequency f of the incident light, giving a straight line.

(b) The experiment is repeated with a metal of **larger** work function. On the same axes, describe how the new line compares with the first. [2]

Exercise 3.5 (b)

3.5 In a photoelectric experiment, the maximum kinetic energy $KE_{\max}$ of the photoelectrons is plotted against the frequency f of the incident light, giving a straight line.

(b) The experiment is repeated with a metal of **larger** work function. On the same axes, describe how the new line compares with the first. [2]

(b) a line with the **same gradient** (parallel to the first), but shifted to the **right** – a **higher threshold frequency** f_0 (and a more negative y -intercept $-\Phi$)

Setup for exercise 3.6

3.6 Light of wavelength 410 nm falls on a clean metal surface in a vacuum photocell. The work function of the metal is 2.3 eV. Take $h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^8 \frac{\text{m}}{\text{s}}$, $e = 1.60 \times 10^{-19}$ C and the electron mass as 9.11×10^{-31} kg.

(a) **State** what is meant by the **work function** of a metal. [1]

(b) **Determine** the energy of one photon, in joules and in electronvolts. [3]

(c) **Determine** the maximum kinetic energy of an emitted electron, and its maximum speed. [3]

Exercise 3.6

(d) **Determine** the threshold wavelength for this metal.

[2]

(e) The **intensity** of the light is doubled, at the same wavelength. **State and explain** the effect on (i) the maximum kinetic energy of the emitted electrons and (ii) the rate at which electrons are emitted.

[3]

(f) **Explain** why the existence of a threshold wavelength cannot be explained by a **wave** model of light.

[2]

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[3]

(f) **Explain** why the existence of a threshold wavelength cannot be explained by a **wave** model of light.

[2]

3.6

(a) the **minimum energy** needed to remove an electron from the surface of the metal

Full solution 3.6 (1/2)

3.6

(a) the **minimum energy** needed to remove an electron from the surface of the metal

(b) $E = hc/\lambda$

$$E = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34} \text{ J s})(3.00 \times 10^8 \frac{\text{m}}{\text{s}})}{410 \times 10^{-9} \text{ m}} = 4.85 \times 10^{-19} \text{ J}$$

$$\frac{4.85 \times 10^{-19} \text{ J}}{1.60 \times 10^{-19} \text{ J eV}^{-1}} = \mathbf{3.0 \text{ eV}}$$

(c) $E_{K,\max} = hf - \phi = 3.03 \text{ eV} - 2.3 \text{ eV} = 0.73 \text{ eV} = 1.17 \times 10^{-19} \text{ J}$

$$v = \sqrt{\frac{2E_K}{m}} = \sqrt{\frac{2 \times 1.17 \times 10^{-19} \text{ J}}{9.11 \times 10^{-31} \text{ kg}}} = \mathbf{5.1 \times 10^5 \frac{\text{m}}{\text{s}}}$$

(d) at the threshold all the photon energy goes into escaping: $\lambda_0 = hc/\phi$

$$\lambda_0 = \frac{hc}{\phi} = \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{(2.3)(1.60 \times 10^{-19})} = 5.4 \times 10^{-7} \text{ m} = \mathbf{540 \text{ nm}}$$

Full solution 3.6 (2/2)

(e) (i) **no change** – the maximum kinetic energy depends only on the photon energy, i.e. on the wavelength, and one electron absorbs one photon

(ii) the rate **doubles**, because twice as many photons arrive each second and each can free one electron

(f) a wave model says energy arrives continuously and spreads over the surface, so any wavelength should eventually free an electron if you wait long enough or make the light bright enough

- in fact **no** electrons are emitted below the threshold however intense the light, which only makes sense if the energy arrives in whole photons of energy hf