

Exercise walk-through

22.2.1

Explaining photoelectric emission, and the stopping-potential experiment

A-Level Physics

You must be able to

- understand that **photoelectrons** may be emitted from a metal surface when it is illuminated
- understand that the **photoelectric effect** provides evidence for a particulate nature of
- recall the terms **threshold frequency** 閾频率 and **threshold wavelength** 閾波长
- understand and use the terms **work function** 逸出功 and **stopping potential** 遏止电压
- **explain photoelectric emission in terms of photon energy and work function energy**
- recall and use $hf = \Phi + \frac{1}{2}mv_{\max}^2$

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The method

Method — The four observations, and why a wave model cannot explain them

When a metal surface is illuminated by electromagnetic radiation, electrons may be emitted from it; these are called **photoelectrons** 光电子. Learn what follows as **four observations and one assumption**, not as a list of facts. The one assumption is: light arrives as **photons** of energy hf , and **one photon gives all of its energy to one electron**. Everything else follows.

- The **work function energy** Φ is the **minimum** energy needed to remove an electron from the surface of the metal. Because one photon must supply it by itself, $hf \geq \Phi$, which is the same as $f \geq f_0$ where $f_0 = \Phi/h$ is the **threshold frequency**. The corresponding **threshold wavelength** is $\lambda_0 = c/f_0 = hc/\Phi$ – and note that a *longer* wavelength means a *lower* frequency, so emission needs $\lambda \leq \lambda_0$.

Method — The four observations, and why a wave model cannot explain them

- Anything left over after paying Φ becomes kinetic energy. An electron deeper in the metal loses more on the way out, so most electrons emerge with **less** than the maximum:

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

- **Intensity is a rate of photons, not an energy per photon.** Doubling the intensity at the same frequency doubles how many electrons come out each second – the **photocurrent** – and changes the energy of each one not at all.

Method — The four observations, and why a wave model cannot explain them

When a metal surface is illuminated by electromagnetic radiation, electrons may be emitted from it; these are...

what is observed	a wave model predicts	the photon model says
1 Below a threshold frequency f_0 <i>no</i> electrons come out, however bright the light.	any frequency should work: just wait until enough energy has arrived. Wrong.	one photon frees one electron, so the <i>single</i> photon must carry at least the work function energy Φ : $hf \geq \Phi$, i.e. $f \geq f_0$.
2 The maximum kinetic energy of the emitted electrons depends on the frequency, not on the brightness.	brighter light carries more energy per second, so the electrons should come out faster. Wrong.	the electron's energy comes from <i>one</i> photon, so it can only depend on that photon's energy hf : $\frac{1}{2}mv_{\max}^2 = hf - \Phi$.
3 Above f_0 , brighter light gives a larger photocurrent .	brighter light should give faster electrons as well as more of them. Only half right.	brighter means <i>more photons per second</i> , so more electrons per second – a larger current, each electron unchanged.
4 Emission begins immediately , even in very faint light.	a faint wave would need minutes to deliver Φ to one electron. Wrong.	energy arrives in whole packets, not as a trickle, so the very first photon to arrive can free an electron at once.

All four follow from *one* assumption: light arrives as **photons** of energy hf , and **one photon gives all its energy to one electron**. Frequency then fixes what each electron gets ($hf - \Phi$) and intensity fixes how many electrons there are.

Method — Evidence both ways: the same light is a wave *and* a particle

- **Interference and diffraction** need a wave: two paths must arrive with a phase difference and cancel or reinforce, which a stream of independent particles cannot do.
- The **photoelectric effect** needs particles: a threshold frequency, an instantaneous start and an energy that depends on frequency only are all wave-proof.
- So neither model alone is the whole story. In an exam, quote the **specific phenomenon** as the evidence – “diffraction shows a wave nature”, “the existence of a threshold frequency shows a particulate nature” – never just “light is both”.

Method — The stopping-potential experiment

- Reverse the p.d. so the collector is **negative**. Each electron now has to climb an energy hill of eV. The current falls to zero when even the **fastest** electron is turned back, so at the **stopping potential** V_s :

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

- **Worked number.** Light of $f = 7.5 \times 10^{14}$ Hz on a metal of $\Phi = 2.1$ eV:

$$hf = 6.63 \times 10^{-34} \times 7.5 \times 10^{14} = 4.97 \times 10^{-19} \text{ J} = 3.11 \text{ eV}$$

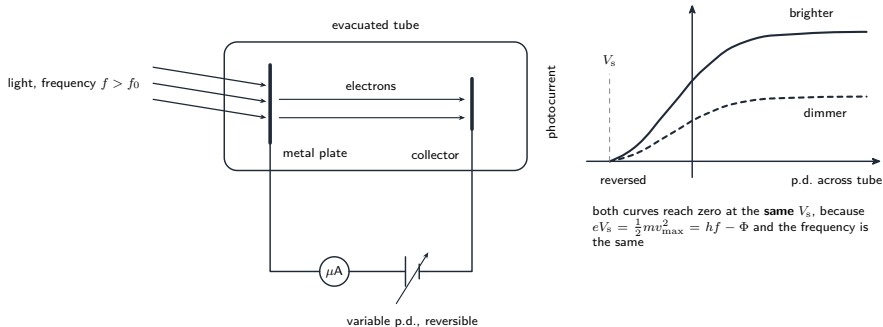
$$\frac{1}{2}mv_{\max}^2 = 3.11 - 2.1 = 1.01 \text{ eV} \quad \Rightarrow \quad V_s = 1.01 \text{ V}.$$

Working in **electronvolts** is what makes this quick: eV_s in eV *is* V_s in volts, so the last step is free. Convert to joules only when the question asks for joules.

Method — The stopping-potential experiment

- Plotting eV_s against f gives a straight line of gradient h and intercept $-\Phi$ on the energy axis, crossing the frequency axis at f_0 . A metal with a larger work function gives a line of the **same gradient**, shifted to the right.

Method — The stopping-potential experiment



Reverse the p.d. until even the fastest electron is turned back: the current falls to zero at the **stopping potential** V_s , and eV_s is the maximum kinetic energy. Making the light brighter raises the saturation current – more electrons per second – but leaves V_s exactly where it was.

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Practice

Practice 2.1 ■ 2 marks

State what is meant by the **work function energy** of a metal.

Solution 2.1

Worked steps

- the **minimum** energy needed (B1)
- to remove an electron from the surface of the metal (B1)
- “the energy needed to free an electron” without “minimum” or “surface” earns one mark only

Practice 2.2 ■ 3 marks

Light is shone on a metal surface. Explain, in terms of photons, why no electrons are emitted when the frequency of the light is below the threshold frequency, however bright the light is.

Solution 2.2

Method: The four observations, and why a wave model cannot explain them — p.4

Worked steps

- one photon gives all of its energy to one electron, so a single photon must supply the whole work function energy by itself (B1)
- the energy of a photon is hf , which depends on the frequency alone (B1)
- below the threshold frequency $hf < \Phi$, so no single photon is enough; making the light brighter sends **more** photons, each one still too weak, so still no emission (B1)

Practice 2.3 ■ 4 marks

Monochromatic light of a frequency above the threshold frequency falls on a metal surface. The intensity of the light is doubled, with the frequency unchanged. State and explain the effect on

Practice 2.3 (a) ■ 2 marks

the maximum kinetic energy of the emitted electrons,

Solution 2.3 (a)

Method: The four observations, and why a wave model cannot explain them — p.4

Worked steps

- **unchanged** (B1)
- the electron's kinetic energy comes from one photon, and the photon energy hf has not changed: $\frac{1}{2}mv_{\text{max}}^2 = hf - \Phi$ (B1)

Practice 2.3 (b) ■ 2 marks

the photocurrent.

Solution 2.3 (b)

Worked steps

- **doubled** B1
- twice the intensity means twice as many photons arriving per second, so twice as many electrons released per second B1

Practice 2.4 ■ 3 marks

Photoelectric emission begins immediately, even when the light is extremely faint. State what a wave model of light predicts instead, and explain why the photon model predicts an immediate start.

Solution 2.4

Method: The four observations, and why a wave model cannot explain them — p.4

Worked steps

- a wave model predicts a **delay**, because a faint wave would deliver energy slowly and the electron would have to absorb it over a long time before it had Φ **B1**
- in the photon model the energy arrives in whole packets, not as a trickle **B1**
- so the very first photon to arrive can free an electron at once, however few photons per second there are **B1**

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Exam-style

Exam-style 3.1 ■ 1 mark

Monochromatic light causes photoelectric emission from a metal surface. The intensity of the light is doubled, with the frequency unchanged. Which row is correct?

	maximum kinetic energy of the electrons	photocurrent
A	unchanged	unchanged
B	unchanged	doubled
C	doubled	unchanged
D	doubled	doubled

Solution 3.1

Method: The four observations, and why a wave model cannot explain them — p.4

Worked steps

B

- doubling the intensity doubles the number of photons per second, not the energy of each one **B1**
- so each electron is unchanged (ruling out **C** and **D**) but there are twice as many per second (ruling out **A**)

Exam-style 3.2 ■ 7 marks

Monochromatic light of frequency 7.5×10^{14} Hz falls on a metal surface of work function energy 2.1 eV.

Exam-style 3.2 (a) ■ 2 marks

Show that the energy of a photon of this light is about 3.1 eV.

Solution 3.2 (a)

Worked steps

$$E = hf = 6.63 \times 10^{-34} \times 7.5 \times 10^{14} = 4.97 \times 10^{-19} \text{ J} \quad \text{M1}$$

$$E = \frac{4.97 \times 10^{-19}}{1.60 \times 10^{-19}} = \mathbf{3.11 \text{ eV}} \approx 3.1 \text{ eV} \quad \text{A1}$$

Exam-style 3.2 (b) ■ 2 marks

Calculate the maximum kinetic energy of an emitted electron, in **joules**.

Solution 3.2 (b)

Worked steps

$$\frac{1}{2}mv_{\max}^2 = hf - \Phi = 3.11 - 2.1 = 1.01 \text{ eV} \quad \text{M1}$$

$$= 1.01 \times 1.60 \times 10^{-19} = \mathbf{1.6 \times 10^{-19} \text{ J}} \quad \text{A1}$$

Exam-style 3.2 (c) ■ 1 mark

Determine the stopping potential for this surface with this light.

Solution 3.2 (c)

Worked steps

■ $eV_s = \frac{1}{2}mv_{\text{max}}^2 = 1.01 \text{ eV}$, so $V_s = 1.0 \text{ V}$ **B1**

Exam-style 3.2 (d) ■ 2 marks

The intensity of the light is halved, with the frequency unchanged.
State and explain the effect on the stopping potential.

Solution 3.2 (d)

Worked steps

- the stopping potential is **unchanged** (B1)
- $eV_s = hf - \Phi$ depends only on the frequency and the metal, and neither has changed; halving the intensity halves the current, not the energy of each electron (B1)

Exam-style 3.3 ■ 10 marks

A student shines light of several different frequencies on a metal surface, measures the stopping potential V_s for each, and plots eV_s against frequency f .

Exam-style 3.3 (a) ■ 2 marks

Use the photoelectric equation to show that $eV_s = hf - \Phi$.

Solution 3.3 (a)

Method: The stopping-potential experiment — p.8

Worked steps

- the fastest electron is just stopped by the reverse p.d., so $eV_s = \frac{1}{2}mv_{\text{max}}^2$ **M1**
- substituting into $hf = \Phi + \frac{1}{2}mv_{\text{max}}^2$ gives $eV_s = hf - \Phi$ **A1**

Exam-style 3.3 (b) ■ 2 marks

State what the **gradient** and the **intercept on the energy axis** of this graph represent.

Solution 3.3 (b)

Worked steps

- the **gradient** is the **Planck constant** h (B1)
- the intercept on the energy axis is $-\Phi$, so its magnitude is the **work function energy** (B1)

Exam-style 3.3 (c) ■ 3 marks

The graph is a straight line of gradient 6.6×10^{-34} Js that crosses the frequency axis at 5.5×10^{14} Hz. Calculate the work function energy of this metal, in eV.

Solution 3.3 (c)

Worked steps

- the line crosses the frequency axis where $eV_s = 0$, so there $hf_0 = \Phi$ M1

$$\Phi = 6.6 \times 10^{-34} \times 5.5 \times 10^{14} = 3.63 \times 10^{-19} \text{ J} \quad \text{M1}$$

$$\Phi = \frac{3.63 \times 10^{-19}}{1.60 \times 10^{-19}} = \mathbf{2.3 \text{ eV}} \quad \text{A1}$$

Exam-style 3.3 (d) ■ 2 marks

The experiment is repeated with a metal of **larger** work function energy. State **two** ways in which the new graph differs from the first.

Solution 3.3 (d)

Worked steps

any **two** of:

- the gradient is the **same**, because the gradient is h and that is a constant of nature **B1**
- the line crosses the frequency axis at a **higher** threshold frequency, i.e. it is shifted to the right **B1**
- the intercept on the energy axis is **more negative**, since it is $-\Phi$
- the two lines are therefore parallel

Exam-style 3.3 (e) ■ 1 mark

Explain why the line does **not** pass through the origin.

Solution 3.3 (e)

Worked steps

- a photon of frequency f has to pay the work function energy Φ before any kinetic energy is left, so at $f = 0$ the line would sit at $-\Phi$, not at zero – there is no emission at all until f reaches f_0 **B1**