# 22.2.1 Explaining photoelectric emission, and the stopping-potential experiment

Name: ____________ Class: ________ Date: __________ **Total: 30 marks**

**KEY WORDS** work function 逸出功 • photoelectric effect 光电效应 • photoelectron 光电子 • threshold frequency 阈频率 • threshold wavelength 阈波长

## Objective

Sheet 22.2 does the **arithmetic** of the photoelectric effect – the equation and the kinetic-energy against frequency graph. This sheet does the part that carries the marks in the written papers: **explaining** photoelectric emission in terms of photon energy and work function energy, saying exactly where a wave model fails, and reading the **stopping-potential** experiment. This sheet covers syllabus 22.2.

**You must be able to:**

- understand that **photoelectrons** may be emitted from a metal surface when it is illuminated by electromagnetic radiation
- understand that the **photoelectric effect** provides evidence for a particulate nature of electromagnetic radiation, while phenomena such as interference and diffraction provide evidence for a wave nature
- recall the terms **threshold frequency** 阈频率 and **threshold wavelength** 阈波长
- 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 $hf = \Phi + \frac{1}{2}mv^2_{\text{max}}$

## 1 Worked examples

Study these first. Each one shows a **method** that a question later on this sheet needs.

### ■ The four observations, and why a wave model cannot explain them

| what is observed | a wave model predicts | the photon model says |
|---|---|---|
| **1** Below a **threshold frequency** $f_0$ *no* 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 *single* photon must carry at least the **work function energy** $\Phi$: $hf \geq \Phi$, 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 *one* photon, so it can only depend on that photon's energy $hf$: $\frac{1}{2}mv^2_{\text{max}} = hf - \Phi$. |
| **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 *more photons per second*, 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 $\Phi$ 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.

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.

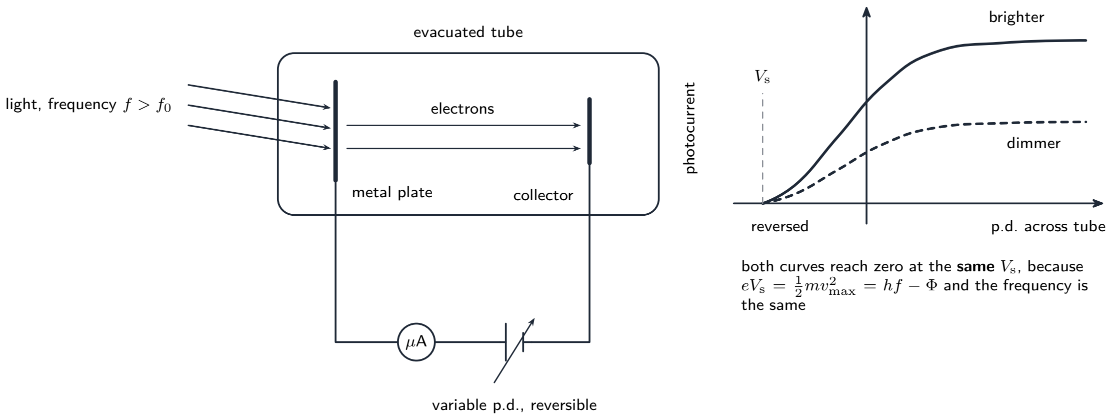
- The **work function energy** $\Phi$ is the **minimum** energy needed to remove an electron from the surface of the metal. Because one photon must supply it by itself, $hf \geq \Phi$, which is the same as $f \geq f_0$ where $f_0 = \Phi/h$ is the **threshold frequency**. The corresponding **threshold wavelength** is $\lambda_0 = c/f_0 = hc/\Phi$ – and note that a *longer* wavelength means a *lower* frequency, so emission needs $\lambda \leq \lambda_0$.
- Anything left over after paying $\Phi$ becomes kinetic energy. An electron deeper in the metal loses more on the way out, so most electrons emerge with **less** than the maximum:
$$hf = \Phi + \tfrac{1}{2}mv^2_{\text{max}}.$$
- **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.

## ■ 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".

### ■ 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.

- 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** $V_s$:

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

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

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

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

  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.
- 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.

## 2 Practice

Now use the methods above.

**2.1** State what is meant by the **work function energy** of a metal. [2]

**2.2** 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. [3]

**2.3** 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

(a) the maximum kinetic energy of the emitted electrons, [2]

(b) the photocurrent. [2]

**2.4** 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. [3]

## 3 Exam-style questions

**3.1** Monochromatic light causes photoelectric emission from a metal surface. The intensity of the light is doubled, with the frequency unchanged. Which row is correct? [1]

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

**3.2** Monochromatic light of frequency $7.5 \times 10^{14}$ Hz falls on a metal surface of work function energy 2.1 eV.

(a) Show that the energy of a photon of this light is about 3.1 eV. [2]

(b) Calculate the maximum kinetic energy of an emitted electron, in **joules**. [2]

(c) Determine the stopping potential for this surface with this light. [1]

(d) The intensity of the light is halved, with the frequency unchanged. State and explain the effect on the stopping potential. [2]

**3.3** 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 $f$.

(a) Use the photoelectric equation to show that $eV_s = hf - \Phi$. [2]

(b) State what the **gradient** and the **intercept on the energy axis** of this graph represent. [2]

(c) The graph is a straight line of gradient $6.6 \times 10^{-34}$ J s that crosses the frequency axis at $5.5 \times 10^{14}$ Hz. Calculate the work function energy of this metal, in eV. [3]

(d) The experiment is repeated with a metal of **larger** work function energy. State **two** ways in which the new graph differs from the first. [2]

(e) Explain why the line does **not** pass through the origin. [1]

## Solutions

Each answer shows the steps, then the **result**.

**2.1**

- the **minimum** energy needed
- to remove an electron from the surface of the metal
- "the energy needed to free an electron" without "minimum" or "surface" earns one mark only

**2.2**

- one photon gives all of its energy to one electron, so a single photon must supply the whole work function energy by itself
- the energy of a photon is $hf$, which depends on the frequency alone
- 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

**2.3**

(a)

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

(b)

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

**2.4**

- 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 $\Phi$
- in the photon model the energy arrives in whole packets, not as a trickle
- so the very first photon to arrive can free an electron at once, however few photons per second there are

**3.1 B**

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

**3.2**

(a)

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

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

(b)

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

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

(c)

- $eV_{\text{s}} = \frac{1}{2}mv_{\text{max}}^2 = 1.01$ eV, so $V_{\text{s}} = \mathbf{1.0}$ V

(d)

- the stopping potential is **unchanged**
- $eV_{\text{s}} = hf - \Phi$ depends only on the frequency and the metal, and neither has changed; halving the intensity halves the current, not the energy of each electron

**3.3**

(a)

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

(b)

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

(c)

- the line crosses the frequency axis where $eV_{\text{s}} = 0$, so there $hf_0 = \Phi$

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

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

(d) any **two** of:

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

(e)

- a photon of frequency $f$ has to pay the work function energy $\Phi$ 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 $f_0$