Photoelectric Effect

Module: The Nature of Light

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Overview

The photoelectric effect is the emission of electrons from a metal surface when illuminated by light of sufficient frequency. This phenomenon provided crucial evidence for the quantum nature of light and earned Einstein the Nobel Prize in 1921.

Key Syllabus Points:

- Investigate evidence that demonstrates inconsistency with the wave model

- Analyse the photoelectric effect using the photon model and conservation of energy
- Apply the equation $K_{\text{max}} = hf - \phi$

Key Concepts

The Phenomenon

Experimental Observations

When light shines on a metal surface: 1. Electrons may be emitted instantly (no time delay) 2. Emission only occurs above a threshold frequency f_0 3. Increasing intensity increases number of electrons, not their energy 4. Increasing frequency increases maximum kinetic energy of electrons

Classical Wave Model Predictions vs Reality

Prediction (Wave Model)	Actual Observation
Any frequency should work if intense enough	Only frequencies above f_0 work
Time delay expected for energy accumulation	Emission is instantaneous
Higher intensity $\rightarrow$ higher electron energy	Higher intensity $\rightarrow$ more electrons only
Higher intensity $\rightarrow$ electron emission	Only frequency determines if emission occurs

Einstein's Photon Model

Key Equation

$$K_{\text{max}} = hf - \phi$$

Where: - K_{max} = maximum kinetic energy of ejected electrons (J) - h = Planck's constant (6.626×10^{-34} J $\cdot$ s) - f = frequency of incident light (Hz) - ϕ = work function of the metal (J)

Einstein's explanation: - Light consists of photons, each with energy $E = hf$ - One photon ejects one electron (one-to-one interaction) - Photon energy must exceed work function for emission - Excess energy becomes kinetic energy

Threshold Frequency

$$f_0 = \frac{\phi}{h}$$

- Below f_0: No electrons emitted regardless of intensity
- Above f_0: Electrons emitted instantly
- At f_0: Electrons emitted with zero kinetic energy

Stopping Voltage

The stopping voltage V_s is the potential difference required to stop the most energetic electrons:

$$K_{\max} = eV_s$$

Therefore: $eV_s = hf - \phi$

Work Function Values

Metal	Work Function (eV)	Threshold Wavelength (nm)
Caesium	2.1	591
Potassium	2.3	539
Sodium	2.4	517
Zinc	4.3	288
Aluminium	4.1	302

Note: 1 eV $= 1.6 \times 10^{-19}$ J

Worked Examples

Example 1: Calculating Maximum Kinetic Energy

Light with frequency 8.0×10^{14} Hz shines on a metal with work function 3.0 eV. Calculate the maximum kinetic energy of ejected electrons.

Solution:

First, convert work function to joules:

$$\phi = 3.0 \times 1.6 \times 10^{-19} = 4.8 \times 10^{-19} \text{ J}$$

Apply photoelectric equation:

$$K_{\text{max}} = hf - \phi$$
$$K_{\text{max}} = (6.626 \times 10^{-34})(8.0 \times 10^{14}) - 4.8 \times 10^{-19}$$
$$K_{\text{max}} = 5.3 \times 10^{-19} - 4.8 \times 10^{-19} = 5.0 \times 10^{-20} \text{ J}$$

Or in eV: $K_{\text{max}} = \frac{5.0 \times 10^{-20}}{1.6 \times 10^{-19}} = 0.31$ eV

Example 2: Finding Threshold Frequency

The stopping voltage for photoelectrons from a certain metal is 1.5 V when illuminated with UV light of wavelength 300 nm. Calculate: (a) The maximum kinetic energy (b) The work function (c) The threshold frequency

Solution:

(a) Maximum kinetic energy:

$$K_{\text{max}} = eV_s = 1.6 \times 10^{-19} \times 1.5 = 2.4 \times 10^{-19} \text{ J}$$

(b) First find photon energy:

$$E = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34})(3 \times 10^8)}{300 \times 10^{-9}} = 6.63 \times 10^{-19} \text{ J}$$

Work function:

$$\phi = hf - K_{\text{max}} = 6.63 \times 10^{-19} - 2.4 \times 10^{-19} = 4.23 \times 10^{-19} \text{ J}$$

(c) Threshold frequency:

$$f_0 = \frac{\phi}{h} = \frac{4.23 \times 10^{-19}}{6.626 \times 10^{-34}} = 6.4 \times 10^{14} \text{ Hz}$$

Common Misconceptions

⚠ Avoid These Mistakes

1. **Intensity affects energy** - Higher intensity means more photons, NOT higher energy photons
2. **Any light works** - Only light above threshold frequency can eject electrons
3. **Time delay** - Emission is instantaneous, not gradual
4. **All electrons same energy** - Electrons have a RANGE of energies up to K_{max}
5. **Forgetting unit conversion** - Work function often given in eV, equation needs joules

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HSC Exam Analysis

Question Types

1. **Calculation questions (4-6 marks)**: Calculate K_{max}, V_s, f_0, or ϕ
2. **Explanation questions (5-7 marks)**: Explain why wave model fails, how photon model succeeds
3. **Graph analysis (4-5 marks)**: Interpret K_{max} vs f or V_s vs f graphs

Graph Analysis

The K_{max} vs f graph is a straight line: - Gradient $= h$ (Planck's constant) - y-intercept $= -\phi$ (negative work function) - x-intercept $= f_0$ (threshold frequency)

Recent HSC Questions

- 2024 Q28: Photoelectric effect calculation and wave/particle comparison
- 2023 Q26: Graph analysis of stopping voltage vs frequency
- 2022 Q25: Explain observations that wave model cannot explain

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Practice Problems

1. UV light of wavelength 250 nm shines on sodium (work function 2.4 eV). Calculate the maximum kinetic energy and stopping voltage.
2. The stopping voltage for a certain metal is 0.8 V for light at 500 nm. Calculate the work function.
3. Explain why increasing the intensity of red light cannot cause electron emission from zinc, but dim UV light can.
4. A photocell has threshold wavelength 540 nm. Calculate the stopping voltage when illuminated with 400 nm light.

Related Topics

- Black Body Radiation
- Wave-Particle Duality
- Special Relativity