PHYS 111
1ST semester 1439-1440

Dr. Nadyah Alanazi

Lecture 22

Chapter 40

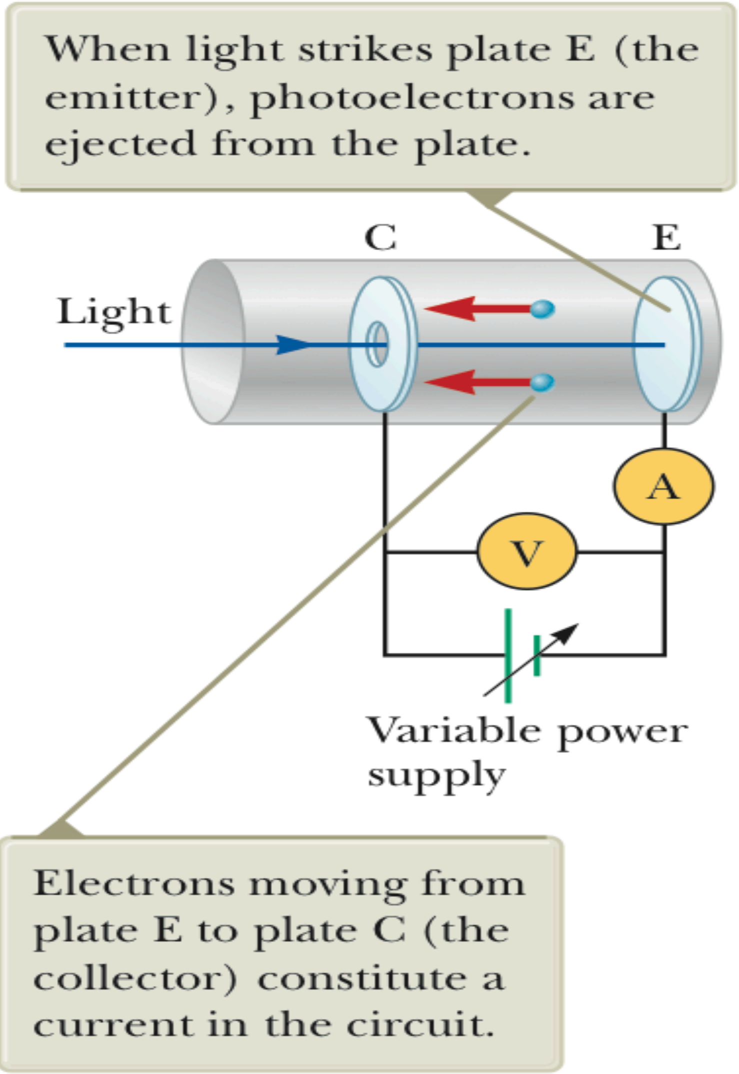
Introduction to Quantum Physics

40.2 The Photoelectric Effect

- Experiments showed that light incident on certain metallic surfaces causes electrons to be emitted from those surfaces.
- This phenomenon is known as the **photoelectric effect,** and the emitted electrons are called **photoelectrons.**

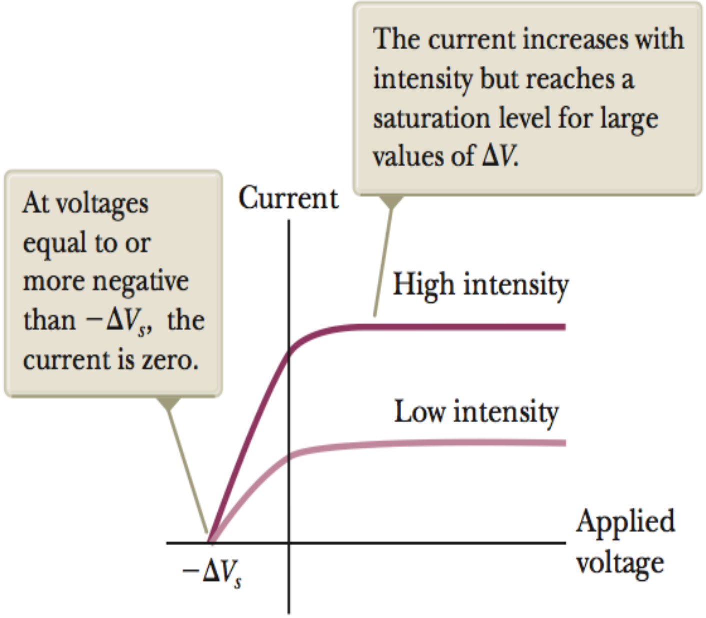
A circuit diagram for studying the photoelectric effect

- When the tube is kept in the dark, the ammeter reads zero.
- When plate E is illuminated by light having an appropriate wavelength, a current is detected by the ammeter.
- The current arises from photoelectrons emitted from the negative plate and collected at the positive plate.



Photoelectric current versus applied potential difference for two light intensities

- At large values of ΔV, the current reaches a maximum value; all the electrons emitted from E are collected at C, and the current cannot increase further.
- The maximum current increases as the intensity of the incident light increases because more electrons are ejected by the higher-intensity light.
- hen ΔV is negative, the battery in the is reversed to make plate E positive and plate C negative, the current drops because many of the photoelectrons emitted from E are repelled by the now negative plate C.
- Only those photoelectrons having a kinetic energy greater than $e|\Delta V|$ reach plate C, where e is the magnitude of the charge on the electron.
- When ΔV is equal to or more negative than $-\Delta V_s$, where ΔV_s is the **stopping potential,** no photoelectrons reach C and the current is zero.



Maximum kinetic energy

- The electron has a maximum kinetic energy upon leaving the metal surface

$$K_{\max} = e\,\Delta V_s$$

- This equation allows us to measure K_{max} experimentally by determining the magnitude of the voltage ΔV_s at which the current drops to zero.

Features of the photoelectric effect

- Dependence of photoelectron kinetic energy on light intensity
  - *Classical Prediction*
    - Electrons should absorb energy continuously from the electromagnetic waves.
    - As the light intensity incident on the metal is increased, the electrons should be ejected with more kinetic energy.
  - *Experimental Result*
    - The maximum kinetic energy is independent of light intensity.
    - The maximum kinetic energy is proportional to the stopping potential (ΔV_s).

Features of the photoelectric effect

- Time interval between incidence of light and ejection of photoelectrons
  - *Classical Prediction*
    - At low light intensities, a measurable time interval should pass between the instant the light is turned on and the time an electron is ejected from the metal.
    - This time interval is required for the electron to absorb the incident radiation before it acquires enough energy to escape from the metal.
  - *Experimental Result*
    - Electrons are emitted almost instantaneously, even at very low light intensities.

Features of the photoelectric effect

- Dependence of ejection of electrons on light frequency
  - *Classical Prediction*
    - Electrons should be ejected at any frequency as long as the light intensity is high enough.
  - *Experimental Result*
    - No electrons are emitted if the incident light falls below some **cutoff frequency, f_c.**
    - The cutoff frequency is characteristic of the material being illuminated.
    - No electrons are ejected below the cutoff frequency regardless of intensity.

Features of the photoelectric effect

- Dependence of photoelectron kinetic energy on light frequency
  - *Classical Prediction*
    - There should be no relationship between the frequency of the light and the electric kinetic energy.
    - The kinetic energy should be related to the intensity of the light.
  - *Experimental Result*
    - The maximum kinetic energy of the photoelectrons increases with increasing light frequency.

Features of the photoelectric effect

- The experimental results contradict all four classical predictions.
- Einstein extended Planck's concept of quantization to electromagnetic waves.
- All electromagnetic radiation of frequency f from any source can be considered a stream of quanta, now called *photons.*
- Each photon has an energy E given by

$$E = hf$$

- and each moves in vacuum with speed of light *c.*
- A photon of incident light gives all its energy hf to a single electron in the metal.

Work function of the metal

- The Electrons ejected from the surface of the metal and not making collisions with other metal atoms before escaping possess the maximum kinetic energy K_{max}.

$$K_{max} = hf - \varphi$$

  - φ is called the work function of the metal.
  - The work function represents the minimum energy with which an electron is bound in the metal.

TABLE 40.1

Work Functions of Selected Metals

Metal	ϕ (eV)
Na	2.46
Al	4.08
Fe	4.50
Cu	4.70
Zn	4.31
Ag	4.73
Pt	6.35
Pb	4.14

Note: Values are typical for metals listed. Actual values may vary depending on whether the metal is a single crystal or polycrystalline. Values may also depend on the face from which electrons are ejected from crystalline metals. Furthermore, different experimental procedures may produce differing values.

Einstein's structural model

- With Einstein's structural model, one can explain the observed features of the photoelectric effect that cannot be understood using classical concepts
  - K_{max} is independent of the light intensity.
  - K_{max} depends only on the light frequency and the work function.
  - Each photon can have sufficient energy to eject an electron immediately.
  - Because the photon must have energy greater than the work function f to eject an electron, the photoelectric effect cannot be observed below a certain cutoff frequency.
  - A photon of higher frequency carries more energy and therefore ejects a photoelectron with more kinetic energy than does a photon of lower frequency.

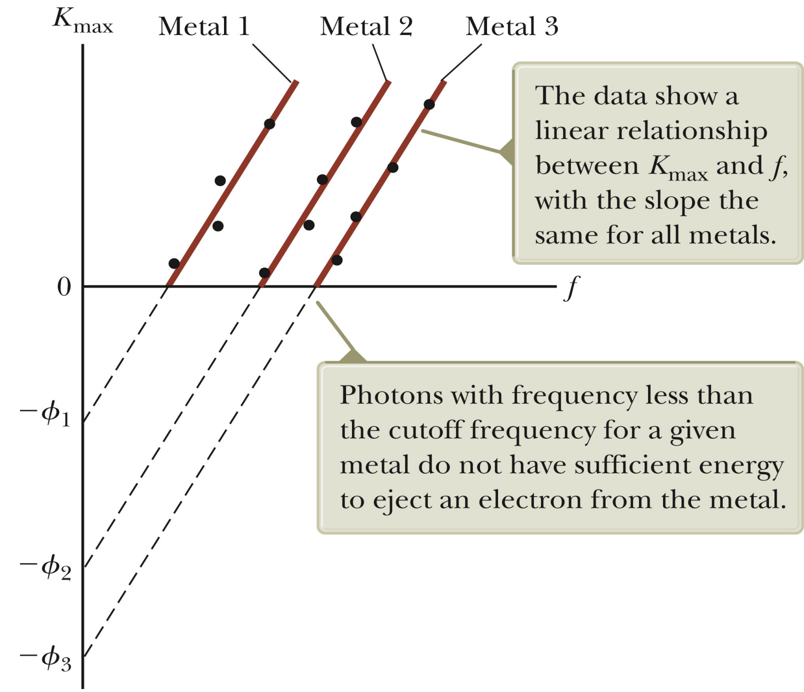
The cutoff frequency

- Einstein's model predicts a linear relationship between the maximum electron kinetic energy K_{max} and the light frequency f.
- The slope of the lines is Planck's constant h.
- The intercept on the horizontal axis gives the cutoff frequency below which no photoelectrons are emitted.
- The cutoff frequency

$$f_c = \phi / h.$$

- The cutoff wavelength

$$\lambda_c = \frac{c}{f_c} = \frac{c}{\phi / h} = \frac{hc}{\phi}$$



$$hc = 1\,240 \text{ eV} \cdot \text{nm}$$

Example 40.3 The Photoelectric Effect for Sodium

A sodium surface is illuminated with light having a wavelength of 300 nm. As indicated in Table 40.1, the work function for sodium metal is 2.46 eV.

(A) Find the maximum kinetic energy of the ejected photoelectrons.

Find the energy of each photon in the illuminating light beam from Equation 40.5:

$$E = hf = \frac{hc}{\lambda}$$

From Equation 40.11, find the maximum kinetic energy of an electron:

$$K_{\max} = \frac{hc}{\lambda} - \phi = \frac{1\,240 \text{ eV} \cdot \text{nm}}{300 \text{ nm}} - 2.46 \text{ eV} = \boxed{1.67 \text{ eV}}$$

(B) Find the cutoff wavelength λ_c for sodium.

SOLUTION

Calculate λ_c using Equation 40.12:

$$\lambda_c = \frac{hc}{\phi} = \frac{1\,240 \text{ eV} \cdot \text{nm}}{2.46 \text{ eV}} = \boxed{504 \text{ nm}}$$