# DUAL NATURE OF RADIATION

## PHOTOELECTRIC EFFECT

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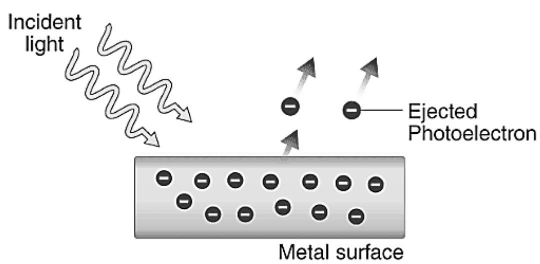
The photoelectric effect is an occurrence in which electrons are expelled from the surface of a metal when it is illuminated with light. These released electrons are termed photoelectrons. It is crucial to emphasize that both the emission of photoelectrons and the kinetic energy of these expelled photoelectrons are contingent on the frequency of the incident light on the metal's surface. The mechanism by which photoelectrons are liberated from the metal's surface due to the impact of light is commonly denoted as photoemission.

The photoelectric effect takes place because electrons situated at the surface of the metal absorb energy from the incoming light. This absorbed energy enables the electrons to surpass the attractive forces holding them to the metallic nuclei. The emission of photoelectrons due to the photoelectric effect can be visualized through the following illustration.




### HISTORY OF THE PHOTOELECTRIC EFFECT

The inception of the photoelectric effect dates back to 1887 when Wilhelm Ludwig Franz Hallwachs first proposed the concept, followed by experimental confirmation by Heinrich Rudolf Hertz. Their observations revealed that when a surface is subjected to electromagnetic radiation surpassing a specific threshold frequency, the radiation gets absorbed, leading to the emission of electrons. In contemporary studies, the photoelectric effect is explored as a phenomenon wherein a material absorbs electromagnetic radiation, subsequently releasing electrically charged particles.

To delve into specifics, the photoelectric effect involves the expulsion of electrons from a metal's surface when illuminated by light. These emitted electrons, aptly termed photoelectrons ($e^-$), contribute to the generation of what is termed photoelectric current.

### EXPLAINING THE PHOTOELECTRIC EFFECT: THE CONCEPT OF PHOTONS

The intricacies of the photoelectric effect elude explanation when light is perceived solely as a wave. However, a comprehensive understanding emerges when light is viewed through the lens of its particle nature, where it manifests as a stream of electromagnetic energy particles known as photons. The energy inherent in a photon correlates with the frequency of the light, a connection encapsulated by Planck's equation:

$E = h\nu = hc/\lambda$

Where,

- $E$ Represents the energy carried by the photon.
- $h$ Signifies Planck's constant.
- $\nu$ Denotes the frequency of the light.
- $c$ Stands for the speed of light in a vacuum.
- $\lambda$ Represents the wavelength of the light.

Hence, it can be comprehended that light of different frequencies transports photons with distinct energies. To illustrate, the frequency of blue light surpasses that of red light, as the wavelength of blue light is considerably shorter than that of red light. Consequently, a photon of blue light possesses more energy than a photon of red light.

## THRESHOLD ENERGY FOR THE PHOTOELECTRIC EFFECT

For the photoelectric effect to take place, the incident photons on the metal surface must carry adequate energy to overcome the attractive forces that bind electrons to the nuclei of the metal. The minimum energy required to liberate an electron from the metal is termed the threshold energy (represented by the symbol Φ). In order for a photon to possess energy equal to the threshold energy, its frequency must match the threshold frequency, which is the minimum frequency of light necessary for the occurrence of the photoelectric effect. The threshold frequency is typically denoted by the symbol $\nu$th, and the associated wavelength, known as the threshold wavelength, is represented by the symbol $\lambda_{th}$. The relationship between the threshold energy and the threshold frequency can be articulated as follows.

$\Phi = h\nu_{th} = hc/\lambda_{th}$

## RELATIONSHIP BETWEEN THE FREQUENCY OF THE INCIDENT PHOTON AND THE KINETIC ENERGY OF THE EMITTED PHOTOELECTRON

Hence, the correlation between the energy of the photon and the kinetic energy of the emitted photoelectron can be expressed as follows.

$E_{photon} = \Phi + E_{electron}$

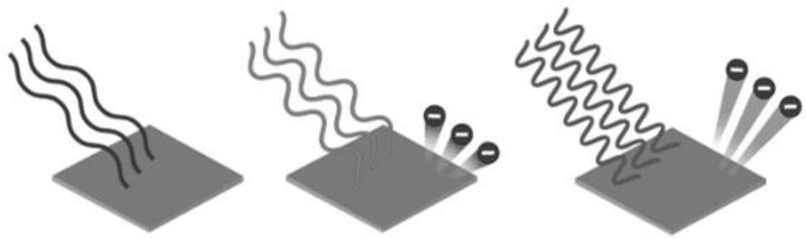
$h\nu = h\nu^{th} + ½m_e v^2$

Where,

Where $E_{photon}$ represents the energy of the incident photon, equivalent to $h\nu$, and Φ represents the threshold energy of the metal surface, equivalent to $h\nu^{th}$.

Eelectron represents the kinetic energy of the photoelectron, equivalent to ½mev$^2$ (where me is the mass of the electron, approximately $9.1 \times 10^{-31}$ kg).

If the energy of the photon is below the threshold energy, no photoelectrons will be emitted due to the inability to overcome the attractive forces between the nuclei and the electrons. In this case, the photoelectric effect will not take place when $\nu < \nu^{th}$. When the frequency of the photon precisely matches the threshold frequency ($\nu = \nu^{th}$), photoelectrons will be emitted, but their kinetic energy will be zero. The impact of the incident light's frequency on the photoelectron's kinetic energy is illustrated below.



Observing the image, it is evident that:

The occurrence of the photoelectric effect is absent when red light impinges upon the metallic surface due to its frequency being lower than the metal's threshold frequency. However, when green light strikes the metallic surface, the photoelectric effect takes place, leading to the emission of photoelectrons.

The photoelectric effect is observed when blue light impinges upon the metallic surface. However, the kinetic energies of the emitted photoelectrons are significantly higher for blue light compared to green light, attributed to the greater frequency of blue light. It's crucial to recognize that the threshold energy differs among metals due to variations in the attractive forces binding electrons to the metal. Additionally, it's noteworthy that the photoelectric effect can occur in non-metals as well, though the threshold frequencies for non-metallic substances are typically very high.

Einstein made significant contributions to our understanding of the photoelectric effect, a phenomenon in which electrons are ejected from a material's surface, typically a metal, when illuminated by light. This effect plays a crucial role in elucidating the quantum nature of both light and electrons.

Following extensive research in this domain, Albert Einstein successfully provided an explanation for the photoelectric effect. He postulated that this phenomenon arose from the discrete, quantized nature of light energy. Einstein's groundbreaking work on the photoelectric effect earned him the prestigious Nobel Prize in Physics in 1921.

According to Einstein's postulation, every photon carrying energy E is

$E = h\nu$

Where

- $E$ Represents the energy of the photon in joules.
- $h$ Is the Planck constant, denoted by $(6.626 \times 10^{-34}\ \mathrm{J.s})$
- $v$ Signifies the frequency of the photon in hertz.

**PROPERTIES OF THE PHOTON**

In the realm of photons, all quantum numbers are null. Devoid of mass and charge, photons exhibit non-reflection in magnetic and electric fields. Their movement transpires at the speed of light in a vacuum. In the context of matter-radiation interaction, radiation assumes the characteristics of tiny particles known as photons. Considered virtual particles, photons demonstrate a direct proportionality between energy and frequency, as well as an inverse proportionality with wavelength. The relationship between the momentum and energy of photons is encapsulated in the following expression:

$E = p.c$

Where

- p denotes the magnitude of the momentum,

- c represents the speed of light.

**DEFINITION OF PHOTOELECTRIC EFFECT**

The occurrence wherein metals emit electrons upon exposure to light of a specific frequency is identified as the photoelectric effect. The electrons liberated in this course of action are referred to as photoelectrons.

Principle of Photoelectric Effect
The photoelectric effect is grounded in the fundamental principle of the conservation of energy.

Minimum Condition for Photoelectric Effect
Threshold Frequency ($\gamma^{\mathrm{th}}$)

The threshold frequency for a given metal refers to the minimum frequency of incident light or radiation required to initiate the photoelectric effect, leading to the ejection of photoelectrons from the metal surface. This threshold frequency is a constant characteristic of a specific metal but can vary among different metals.

If $\gamma$ represents the frequency of the incident photon and $\gamma^{\mathrm{th}}$ denotes the threshold frequency, then,

If $\gamma < \gamma^{th}$, there will be no ejection of photoelectrons, and consequently, no photoelectric effect occurs.

When $\gamma = \gamma^{th}$, photoelectrons are just ejected from the metal surface, and in this scenario, the kinetic energy of the electron is zero.

If $\gamma > \gamma^{th}$, photoelectrons will be emitted from the surface along with kinetic energy. Now, let's discuss the concept of the threshold wavelength ($\lambda^{\text{th}}$).

During the emission of electrons, the specific wavelength of incident light corresponding to the longest wavelength is referred to as the threshold wavelength for a metal surface.

$\lambda^{th} = \text{c}/\gamma^{th}$

For wavelengths beyond this threshold, there will be no emission of photoelectrons. If λ represents the wavelength of the incident photon, then:

If $\gamma = \gamma^{th}$, the photoelectric effect will occur, and the ejected electron will possess kinetic energy.

If $\gamma = \gamma^{th}$, only the photoelectric effect will take place, and the kinetic energy of the ejected photoelectron will be zero.

If $\gamma > \gamma^{th}$, there will be no photoelectric effect.

**PHOTOELECTRIC EFFECT FORMULA**
**ACCORDING TO EINSTEIN'S EXPLANATION OF THE PHOTOELECTRIC EFFECT:**

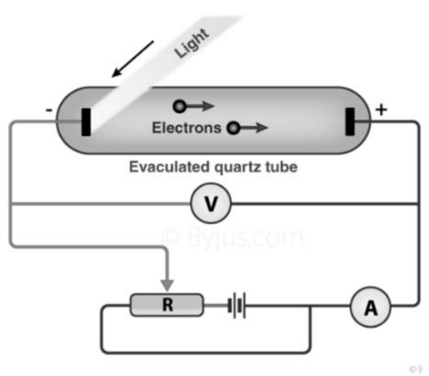
The energy of the photon is = the energy needed to remove an electron + the kinetic energy of the emitted electronlike.

i.e. $\text{h}\nu = \text{W} + \text{E}$

Where
$h$ represents Planck's constant.
$\nu$ stands for the frequency of the incident photon.
$W$ denotes the work function.
$E$ Represents the maximum kinetic energy of the ejected electrons, given by the expression$1/2mv^2$.

**Experimental Study of Photoelectric Effect**

The given experiment is used to study the photoelectric effect experimentally. In an evacuated glass tube, two zinc plates C and D are enclosed. Plates C acts as anode and D act as a photosensitive plate.




Photoelectric Effect: Experimental Setup

In the experimental setup, two plates, denoted as C and D, are integrated into a circuit connected to a battery (B) and an ammeter (A). Plate D, exposed to radiation through a quartz window (W), experiences the emission of electrons, resulting in the flow of current in the circuit. This electric current generated by the ejection of electrons is termed photocurrent. Additionally, plate C has the capability to be adjusted to a desired potential, either positive or negative, in relation to plate D.

## CHARACTERISTICS OF PHOTOELECTRIC EFFECT

The threshold frequency exhibits variation depending on the material and differs across various substances. The photoelectric current maintains a direct proportionality to the intensity of the incident light. The kinetic energy of the emitted photoelectrons demonstrates a direct correlation with the frequency of the incident light. Furthermore, the stopping potential directly corresponds to the frequency, and the entire process occurs instantaneously.

## Applications of Photoelectric Effect

The application of the photoelectric effect is diverse and spans various technological and scientific fields:

1. Solar Panels for Electricity Generation: Photoelectric materials in solar panels facilitate the generation of electricity across a broad spectrum of wavelengths.

2. Motion and Position Sensors: Utilizing a photoelectric material placed in front of a UV or IR LED, motion and position sensors detect changes in potential difference when an object interrupts the light path between the LED and sensor.

3. Lighting Sensors in Smartphones: Photoelectric sensors in smartphones adjust screen brightness automatically based on the intensity of light hitting the sensor.

4. Digital Cameras: Photoelectric sensors in digital cameras detect and record light, allowing for the capture of different colors.

5. X-Ray Photoelectron Spectroscopy (XPS): Employing x-rays to irradiate a surface and measuring the kinetic energies of emitted electrons, XPS provides insights into surface chemistry, including elemental and chemical composition.

6. Burglar Alarms: Photoelectric cells play a crucial role in burglar alarms, detecting changes in light conditions.

7. Photomultipliers: Utilized to detect low levels of light, photomultipliers rely on the photoelectric effect.

8. Video Camera Tubes: In the early days of television, photoelectric cells were used in video camera tubes.

9. Night Vision Devices: The photoelectric effect contributes to the functioning of night vision devices.

10. Chemical Analysis: The photoelectric effect aids in the chemical analysis of materials, as emitted electrons carry specific energies characteristic of the atomic source.

## PROBLEMS ON PHOTOELECTRIC EFFECT

**Example.**

In a photoelectric experiment, the special wavelength of light needed to start the effect is 260 nanometers. There's a formula that connects the energy (in electron volts) with the wavelength: $E = \frac{1237}{\lambda}$ (where λ is the wavelength). Now, figure out the maximum kinetic energy of the electrons that are released.

**Solution.**

$$K_{max} = \frac{hc}{\lambda} - \frac{hc}{\lambda 0} = hc \times \left[\frac{\lambda 0 - \lambda}{\lambda\lambda 0}\right]$$

$$K_{max} = (1237) \times \left[\frac{380 - 260}{380} \times 260\right] = 1.5 \text{ eV}$$

Hence, the maximum kinetic energy of the electrons emitted in the photoelectric effect is 1.5 eV.

**Example.**

In a photoelectric experiment, if the wavelength of the incident light changes from 300 nm to 400 nm, and we use the constant (hc/e = 1240 nm-V), we need to find the decrease in the stopping potential.

**Solution.**

$$\frac{hc}{\lambda_1} = \phi + eV_1 \quad \text{. . . . (i)}$$

$$\frac{hc}{\lambda_2} = \phi + eV_2 \quad \text{. . . . (ii)}$$

Equation (i) – (ii)

$$hc\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) = e \times (V1 - V2)$$

$$V_1 - V_2 = \left(\frac{hc}{e}\right) \times \left[\frac{\lambda_2 - \lambda_1}{\lambda_1\lambda_2}\right]$$

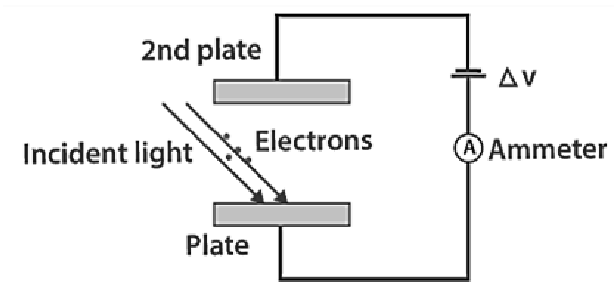
$$(1240 \text{ nm V}) \times \frac{100\text{nm}}{300\text{nm} \times 400\text{nm}}$$

$\frac{12.4}{12} \approx$ 1v.

Hence, the reduction in the stopping potential observed in the photoelectric experiment amounts to 1 volt.

**Example.**

When a metal plate is exposed to ultraviolet light with a 230 nm wavelength, electrons are released from plate 1. These electrons move across a gap to plate 2, generating a current in the wire connecting the two plates. The voltage of the battery is then increased until the ammeter reads zero current, reaching a voltage of 1.30 V.




**a)** Determine the energy of the photons in the light beam in electron volts (eV).
**b)** Calculate the maximum kinetic energy of the emitted electrons in electron volts (eV).

**Solution.**

Assuming that the wavelength corresponds to the wavelength in a vacuum

$$f = \frac{c}{x}$$

$$f = \frac{3\times10^{8}}{2.40\times10^{15}\,HZ}$$

The energy of a photon, E, is given by the formula E = hf.

E = $(4.136 \times 10^{-15})$ $(1.25 \times 10^{15})$

Note: Planck's constant in eV s = $4.136 \times 10^{-15}$ eV s

E = 5.17 eV.

b) The maximum kinetic energy associated with the emitted electrons is determined by the stopping potential. In this scenario, the stopping potential is 1.30V. Therefore, the maximum kinetic energy of the electrons is 1.30 electronvolts (eV).

## INTERESTING POINTS TO REMEMBER

- When considering light with a specific frequency, the photoelectric current tends to be directly proportional to the intensity of light, provided that the frequency is above the threshold frequency.

- Below the threshold frequency, even with high-intensity incident light, the emission of photoelectrons comes to a complete halt.

- The maximum kinetic energy of a photoelectron increases with the frequency of incident light, but this is only applicable when the frequency surpasses the threshold limit. The maximum kinetic energy remains unaffected by the intensity of light.

- Stopping potential refers to the negative potential applied to the opposite electrode when the photoelectric current reaches zero.

- The threshold frequency is the frequency at which the photoelectric current ceases for incident light below a specific frequency.

- The photoelectric effect serves as evidence supporting the quantum nature of radiation and is indicative of the particle nature of light.