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Review Article

THE PHOTOELECTRIC EFFECT: A MINI REVIEW

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ABSTRACT

The photoelectric effect, a pivotal discovery in the realm of quantum physics, sheds light on the intriguing behavior of light and electrons. First observed by Heinrich Hertz in 1887, it was Albert Einstein's groundbreaking interpretation in 1905 that revolutionized our understanding. The phenomenon occurs when light, typically in the form of photons, strikes the surface of a material, causing the emission of electrons. What makes the photoelectric effect particularly fascinating is its insistence on a threshold frequency for electron emission. Below this frequency, regardless of how intense the light is, no electrons are liberated. This observation challenged classical wave theories that predicted a gradual increase in energy with the amplitude of the wave. Einstein proposed a bold solution, suggesting that light is quantized into discrete packets of energy, each known as a photon. The energy of these photons is directly proportional to their frequency, aligning with Max Planck's earlier work on quantized energy levels. The photoelectric effect, with its instantaneous emission of electrons upon light exposure, served as compelling evidence for the wave-particle duality of light. Practical applications abound, with the photoelectric effect forming the basis of photovoltaic cells that convert sunlight into electrical energy. Moreover, its utilization of technologies such as photomultiplier tubes and various light detectors underscores its crucial role in scientific research and technological advancements. The photoelectric effect, once a perplexing anomaly, now stands as a cornerstone in the edifice of quantum mechanics, guiding both theoretical as well as practical understanding.

Keywords: *Electron Emission, Threshold energy, Photons, Quantum Mechanics*

INTRODUCTION

The phenomena of metals releasing electrons when they are exposed to the light of the appropriate frequency is called the photoelectric effect, and the electrons emitted during the process are called photoelectrons (Qian, et al., 2023). The photoelectric effect occurs because the electrons at the surface of the metal tend to absorb energy from the incident light and use it to overcome the attractive forces that bind them to the metallic nuclei. The photoelectric effect was first introduced by Wilhelm Ludwig Franz Hallwachs in the year 1887, and the experimental verification was done by Heinrich Rudolf

Hertz (Jho, et al., 2023). They observed that when a surface is exposed to electromagnetic radiation at a higher threshold frequency, the radiation is absorbed, and the electrons are emitted. Today, we study the photoelectric effect as a phenomenon that involves a material absorbing electromagnetic radiation and releasing electrically charged particles (Peng, et al., 2023). To be more precise, light incident on the surface of a metal in the photoelectric effect causes electrons to be ejected. The electron ejected due to the photoelectric effect is called a photoelectron and is denoted by e^-. The current produced as a result of the ejected electrons is called photoelectric current (Prayogi, et al., 2023).

The Concept of Photons

It can be explained by the particle nature of light, in which light can be visualised as a stream of particles of electromagnetic energy (Kumar et al., 2023). These 'particles' of light are called photons. The energy held by a photon is related to the frequency of the light via Planck's equation.

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

Where,

- E denotes the energy of the photon
- h is Planck's constant
- ν denotes the frequency of the light
- c is the speed of light (in a vacuum)
- λ is the wavelength of the light

Thus, it can be understood that different frequencies of light carry photons of varying energies. For example, the frequency of blue light is greater than that of red light (the wavelength of blue light is much shorter than the wavelength of red light). Therefore, the energy held by a photon of blue light will be greater than the energy held by a photon of red light (Juandi et al., 2023).

Threshold Energy for the Photoelectric Effect

For the photoelectric effect to occur, the photons that are incident on the surface of the metal must carry sufficient energy to overcome the attractive forces that bind the electrons to the nuclei of the metals (Jie, et al., 2023). The minimum amount of energy required to remove an electron from the metal is called the threshold energy (denoted by the symbol Φ). For a photon to possess energy equal to the threshold energy, its frequency must be equal to the threshold frequency (which is the minimum frequency of light required for the photoelectric effect to occur). The threshold frequency is usually denoted by the symbol ν_{th}, and the associated wavelength (called the threshold wavelength) is denoted by the symbol λ_{th}. The relationship between the threshold energy and the threshold frequency can be expressed as follows (Pei-Pei, et al., 2023).

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

Relationship between the Frequency of the Incident Photon and the Kinetic Energy of the Emitted Photoelectron

Therefore, the relationship between the energy of the photon and the kinetic energy of the emitted photoelectron can be written as follows:

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

$$\Rightarrow h\nu = h\nu_{th} + ½m_e v^2$$

Where,

- E_{photon} denotes the energy of the incident photon, which is equal to $h\nu$
- Φ denotes the threshold energy of the metal surface, which is equal to $h\nu_{th}$
- $E_{electron}$ denotes the kinetic energy of the photoelectron, which is equal to $½m_e v^2$ (m_e = Mass of electron = $9.1*10^{-31}$ kg)

If the energy of the photon is less than the threshold energy, there will be no emission of photoelectrons (since the attractive forces between the nuclei and the electrons cannot be overcome). Thus, the photoelectric effect will not occur if $\nu < \nu_{th}$. If the frequency of the photon is exactly equal to the threshold frequency ($\nu = \nu_{th}$), there will be an emission of photoelectrons, but their kinetic energy will be equal to zero. An illustration detailing the effect of the frequency of the incident light on the kinetic energy of the photoelectron is provided below (Karpeshin, et al., 2023).

It is important to note that the threshold energy varies from metal to metal. This is because the attractive forces that bind the electrons to the metal are different for different metals (López-Segovia, et al., 2023). It can also be noted that the photoelectric effect can also take place in non-metals, but the threshold frequencies of non-metallic substances are usually very high.

Einstein's Contributions towards the Photoelectric Effect

The photoelectric effect is the process that involves the ejection or release of electrons from the surface of materials (generally a metal) when light falls on them. The photoelectric effect is an important concept that enables us to clearly understand the quantum nature of light and electrons (Zhang, et al., 2023). After continuous research in this field, the explanation for the photoelectric effect was successfully explained by Albert Einstein. He concluded that this effect occurred as a result of light energy being carried in discrete quantised packets. For this excellent work, he was honoured with the Nobel Prize in 1921. According to Einstein, each photon of energy E is

$$E = h\nu$$

Where E = Energy of the photon in joule, h = Plank's constant (6.626×10^{-34} J.s)

ν = Frequency of photon in Hz

The momentum and energy of the photons are related, $E = p.c$ where

p = Magnitude of the momentum; c = Speed of light

Minimum Condition for Photoelectric Effect

- ✓ **Threshold Frequency (γ_{th})**

It is the minimum frequency of the incident light or radiation that will produce a photoelectric effect, i.e., the ejection of photoelectrons from a metal surface is known as the threshold frequency for the metal (Lee et al., 2023). It is constant for a specific metal but may be different for different metals.

If γ = Frequency of the incident photon and γ_{th}= Threshold frequency, then,

- If $\gamma < \gamma_{Th}$, there will be no ejection of photoelectron and, therefore, no photoelectric effect.
- If $\gamma = \gamma_{Th}$, photoelectrons are just ejected from the metal surface; in this case, the kinetic energy of the electron is zero.
- If $\gamma > \gamma_{Th}$, then photoelectrons will come out of the surface, along with kinetic energy.

- ✓ **1.3.5.2 Threshold Wavelength (λ_{th})**

During the emission of electrons, a metal surface corresponding to the greatest wavelength to incident light is known as threshold wavelength (Guo, et al., 2023).

$$\lambda_{th} = c/\gamma_{th}$$

For wavelengths above this threshold, there will be no photoelectron emission. For λ = wavelength of the incident photon, then

- If $\lambda < \lambda_{Th}$, then the photoelectric effect will take place, and ejected electron will possess kinetic energy (Rincon, et al., 2023).
- If $\lambda = \lambda_{Th}$, then just the photoelectric effect will take place, and the

kinetic energy of ejected photoelectron will be zero.

- If $\lambda > \lambda_{Th,}$ there will be no photoelectric effect (Fitri, et al., 2023).

✓ **1.3.5.3 Work Function or Threshold Energy (Φ)**

The minimal energy of thermodynamic work that is needed to remove an electron from a conductor to a point in the vacuum immediately outside the surface of the conductor is known as work function/threshold energy (Purwahida, et al., 2023).

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

The work function is the characteristic of a given metal. If E = energy of an incident photon, then

1. *If E < Φ, no photoelectric effect will take place.*
2. *If E = Φ, just a photoelectric effect will take place, but the kinetic energy of ejected photoelectron will be zero*
3. *If E > photoelectron will be zero*
4. *If E > Φ, the photoelectric effect will take place along with the possession of the kinetic energy by the ejected electron (*Nan, et al., 2023).

Photoelectric Effect Formula

According to Einstein's explanation of the photoelectric effect,

The energy of photon = Energy needed to remove an electron + Kinetic energy of the emitted electron

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

Where,

- h is Planck's constant
- ν is the frequency of the incident photon
- W is a work function
- E is the maximum kinetic energy of ejected electrons: $1/2\ mv^2$

Laws Governing the Photoelectric Effect

- For a light of any given frequency,; ($\gamma > \gamma_{Th}$), the photoelectric current is directly proportional to the intensity of light (Zhong, et al., 2023).
- For any given material, there is a certain minimum (energy) frequency, called threshold frequency, below which the emission of photoelectrons stops completely, no matter how high the intensity of incident light is (dos Santos, et al., 2023).

- The maximum kinetic energy of the photoelectrons is found to increase with the increase in the frequency of incident light, provided the frequency ($\gamma > \gamma_{Th}$) exceeds the threshold limit (Li, et al., 2023). The maximum kinetic energy is independent of the intensity of light.
- The photo-emission is an instantaneous process.

Factors Affecting the Photoelectric Effect

✓ **Effects of Intensity of Incident Radiation on Photoelectric Effect**

The potential difference between the metal plate, collector and frequency of incident light is kept constant, and the intensity of light is varied (Liu et al., 2023). The electrode C, i.e., the collecting electrode, is made positive with respect to D (metal plate). For a fixed value of frequency and the potential between the metal plate and collector, the photoelectric current is noted in accordance with the intensity of incident radiation (Fiolhais, et al., 2023). It shows that photoelectric current and intensity of incident radiation both are proportional to each other. The photoelectric current gives an account of the number of photoelectrons ejected per sec (Życki, et al., 2023).

✓ **Effects of Potential Difference between the Metal Plate and the Collector on the Photoelectric Effect**

The frequency of incident light and intensity is kept constant, and the potential difference between the plates is varied. Keeping the intensity and frequency of light constant, the positive potential of C is increased gradually (Zhao et al., 2023). Photoelectric current increases when there is a positive increase in the potential between the metal plate and the collector up to a characteristic value. There is no change in photoelectric current when the potential is increased higher than the characteristic value for any increase in the accelerating voltage. This maximum value of the current is called saturation current (Wang, et al., 2023).

Effect of Frequency on Photoelectric Effect

The intensity of light is kept constant, and the frequency of light is varied. For a fixed intensity of incident light, variation in the frequency of incident light produces a linear variation of the cut-off potential/stopping potential of the metal (Sauerheber, et al., 2023). It is shown that the cut-off potential (Vc) is linearly proportional to the frequency of incident light. The kinetic energy of the photoelectrons increases directly proportionally to the frequency of incident light to completely stop the photoelectrons (Wieman et al., 2023). We should reverse and increase the potential between the metal plate and collector in (negative value) so the emitted photoelectron can't reach the collector.

Einstein's Photoelectric Equation

According to Einstein's theory of the photoelectric effect, when a photon collides inelastically with electrons, the photon is absorbed completely or partially by the electrons (Feng, et al., 2023). So if an electron in a metal absorbs a photon of energy, it uses the energy in the following ways. Some energy Φ_0 is used in making the surface electron free from the metal. It is known as the work function of the material. Rest energy will appear as kinetic energy (K) of the emitted photoelectrons (Tan et al., 2023).

- ✓ **Photoelectric Equation Explains the Following Concepts**

- The frequency of the incident light is directly proportional to the kinetic energy of the electrons, and the wavelengths of incident light are inversely proportional to the kinetic energy of the electrons (Wang et al., 2023).
- If $\gamma = \gamma_{th}$ or $\lambda = \lambda_{th}$ then $v_{max} = 0$
- $\gamma < \gamma_{th}$ or $\lambda > \lambda_{th}$: There will be no emission of photoelectrons.
- The intensity of the radiation or incident light refers to the number of photons in the light beam. More intensity means more photons and vice-versa. Intensity has nothing to do with the energy of the photon (Cao, et al., 2023). Therefore, the intensity of the radiation is increased, and the rate of emission increases, but there will be no change in the kinetic energy of electrons. With an increasing number of emitted electrons, the value of the photoelectric current increases.

Applications of Photoelectric effect

The photoelectric effect, a fundamental phenomenon in physics, has found diverse applications across various technological and scientific domains

(Tong, et al., 2023). Perhaps most notably, the principle underlies the operation of photovoltaic cells, commonly known as solar cells. In these cells, the photoelectric effect is harnessed to convert sunlight into electricity, providing a sustainable and clean energy source (Jiang, et al., 2023). Additionally, the photoelectric effect is integral to the functioning of photomultiplier tubes, sensitive light detectors widely used in scientific instruments such as spectrophotometers and particle detectors (Yang, et al., 2023). In industrial settings, light sensors and detectors capitalize on the photoelectric effect, playing crucial roles in automation, robotics, and security systems. Image sensors in cameras, employing charge-coupled devices (CCDs) and complementary metal-oxide-semiconductor (CMOS) technology, utilize the photoelectric effect to capture and convert light into electrical signals, enabling digital imaging (Chen, et al., 2023). Medical imaging techniques, particularly X-ray imaging, leverage the photoelectric effect to create detailed images of internal structures within the human body (Pacala et al., 2023). Moreover, surface analysis techniques like photoelectron spectroscopy and Auger electron spectroscopy rely on the photoelectric effect to provide insights into material composition and electronic structure. Even in everyday devices like ionization smoke detectors, the photoelectric effect is applied to sense smoke particles through the ionization caused by alpha particles (Cheng, et al., 2023). These varied applications underscore the versatility and significance of the photoelectric effect in shaping technological advancements and scientific research.

CONCLUSION

The photoelectric effect, originating in the early 20th century, is a fundamental principle with extensive uses and bright prospects for the future. With the progress of technology, the photoelectric effect has expanded its reach into other fields, providing novel and creative solutions. A prominent field of study is renewable energy, namely photovoltaic cells that utilise the photoelectric effect to transform sunlight into electrical energy. Continuing research endeavours aim to improve the effectiveness and cost-effectiveness of solar technology, therefore facilitating the development of a more environmentally-friendly energy future. Furthermore, progress in the field of materials science and nanotechnology exploits the photoelectric effect to create innovative sensors, detectors, and imaging systems. Quantum computing investigates the deliberate control of electrons using the principles of the photoelectric effect to develop computer systems that are faster and more efficient. With the ongoing advancement of technology, the photoelectric effect continues to play a crucial role in driving innovative progress in the fields of energy, electronics, and other related areas. The future applications of this technology have the potential to completely transform industries and effectively tackle urgent global concerns.

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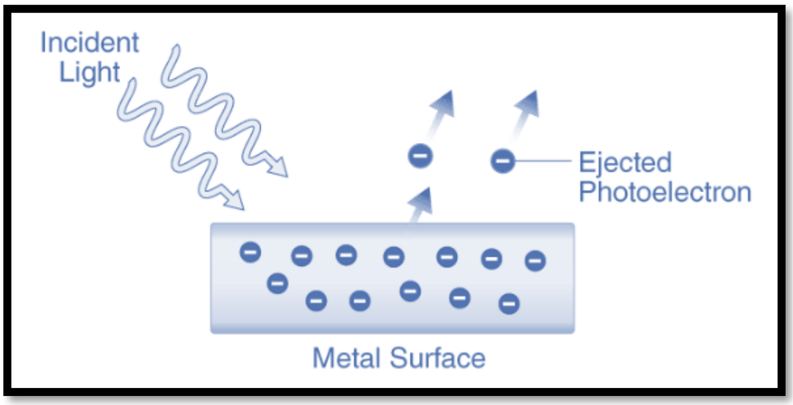

Figure 1: The emission of photoelectrons as a result of the photoelectric effect

Properties of the Photon

- For a photon, all the quantum numbers are zero.
- A photon does not have any mass or charge, and they are not reflected in a magnetic and electric field.
- The photon moves at the speed of light in empty space.
- During the interaction of matter with radiation, radiation behaves as it is made up of small particles called photons.
- Photons are virtual particles. The photon energy is directly proportional to its frequency and inversely proportional to its wavelength.

Figure 2: Figure depicting Properties of a Photon

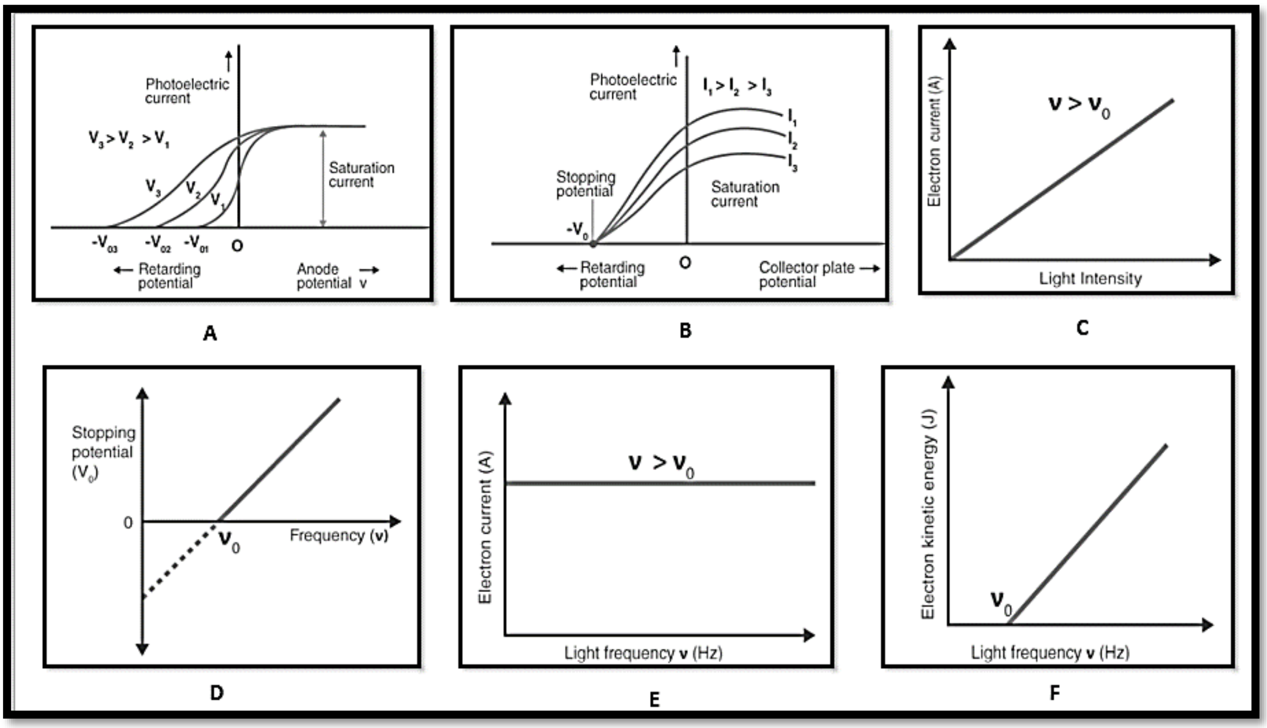

Figure 3: Different Graphs of the Photoelectric Equation

A. **Photoelectric current vs Retarding potential for different voltages**
B. **Photoelectric current vs Retarding potential for different intensities**
C. **Electron current vs Light Intensity**
D. **Stopping potential vs Frequency**
E. **Electron current vs Light frequency**
F. **Electron kinetic energy vs Light frequency**

Table 1: Applications of the Photoelectric Effect

Application	Description
Photovoltaic Cells (Solar Cells)	Converts sunlight into electricity by utilizing the photoelectric effect in semiconductor materials.
Photomultiplier Tubes	Sensitive light detectors amplifying and detecting faint light signals, commonly used in scientific instruments.
Light Sensors and Detectors	Converts light signals into electrical signals, employed in automation, robotics, security systems, and industrial control.
Image Sensors in Cameras	CCDs and CMOS image sensors use the photoelectric effect to convert light into electrical signals for digital imaging.
Medical Imaging	Applied in X-ray imaging, where X-rays interacting with materials cause the emission of photoelectrons for detailed imaging.
Surface Analysis Techniques	Photoelectron spectroscopy and Auger electron spectroscopy analyze material composition and electronic structure.
Ionization Smoke Detectors	Uses the photoelectric effect to detect smoke particles through ionization caused by alpha particles.