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QUANTUM THEORY OF RADIATION AND ITS APPLICATIONS

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Abstract:
The photoelectric effect refers to what happens when electrons are emitted from a material that has absorbed electromagnetic radiation. Physicist Albert Einstein was the first to describe the effect fully, and received a Nobel Prize for his work. Light with energy above a certain point can be used to knock metal electron loose freeing them from a solid metal surface, according to Scientific American. Each particle of light, called a photon, collides with an electron and uses some of its energy to dislodge the electron. The rest of the photon's energy transfers to the free negative charge, called a photoelectron Solar Panels use it to generate power. Metal combinations in these panels allow power to be generated from a wide variety of wavelengths.

Keywords:
Electromagnetic, radiation, photoelectron.

Discovery
Before Einstein, the effect had been observed by scientists, but they were confused by the behavior because they didn't fully understand the nature of light. In the late 1800s, physicists James Clerk Maxwell in Scotland and Hendrik Lorentz in the Netherlands determined that light appears to behave as a wave. This was proven by seeing how light waves demonstrate interference, diffraction and scattering, which are common to all sorts of waves (including waves in water.)For example, Heinrich Hertz of Germany was the first person to see the photoelectric effect, in 1887. He discovered that if he shone ultraviolet light onto metal electrodes, he lowered the voltage needed to make a spark move behind the electrodes, according to English astronomer David Darling.

Then in 1899, in England, J.J. Thompson demonstrated that ultraviolet light hitting a metal surface caused the ejection of electrons. A quantitative measure of the photoelectric effect came in 1902, with work by Philipp Lenard (a former assistant to Hertz.) It was clear that light had electrical properties, but what was going on was unclear.

According to Einstein, light is made up of little packets, at first called quanta and later photons. How quanta behave under the photoelectric effect can be understood through a thought experiment. Imagine a marble circling in a well, which would be like a bound electron to an atom. When a photon comes in, it hits the marble (or electron), giving it enough energy to escape from the well. This explains the behavior of light striking metal surfaces.

While Einstein, then a young patent clerk in Switzerland, explained the phenomenon in 1905, it took 16 more years for the Nobel Prize to be awarded for his work. This came after American physicist Robert Millikan not only verified the work, but also found a relation between one of Einstein's constants and Planck's constant. The latter constant describes how particles and waves behave in the atomic world.

Further early theoretical studies on the photoelectric effect were performed by Arthur Compton in 1922 (who showed that X-rays also could be treated as photons and earned the Nobel Prize in 1927), as well as Ralph Howard Fowler in 1931 (who looked at the relationship between metal temperatures and photoelectric currents.)
wave nature of radiation suggests that energy is emitted or observed continuously as electromagnetic waves. However, wave nature of radiation cannot explain the experimentally observed phenomena like photonupon it is called photoelectric effect. These electrons are called photoelectrons.

Metals like Zinc, Cadmium etc are more sensitive only to ultraviolet rays whereas alkali metals like Sodium, Potassium etc are sensitive even to visible light.

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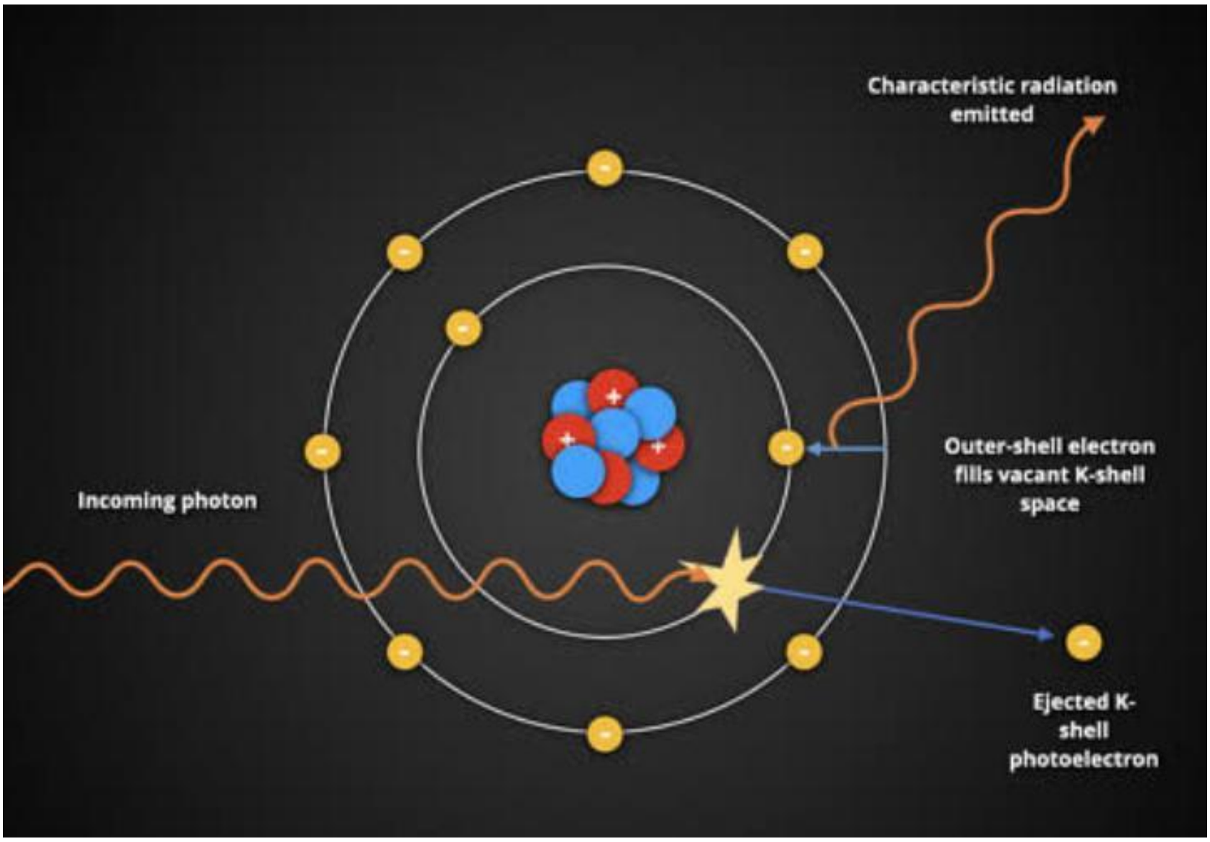
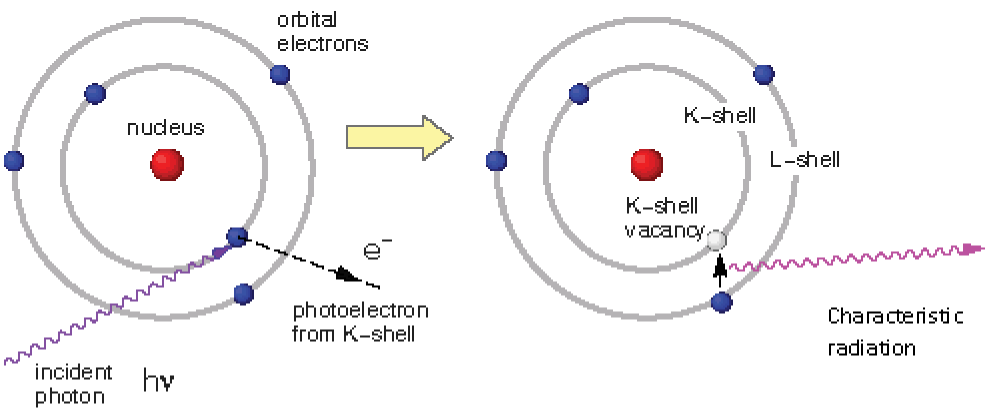


Quantum Theory of Radiation

According to the quantum theory of radiation, the energy from the body is emitted in separate packets of energy each packet is called a quantum of energy. Each quantum carries a definite amount of energy called a photon. Therefore, the energy carried by each photon is given by:

E=hf

Where, f is the frequency of radiation and h is a Planck constant whose value is 6.62×10^{-34} joule sec.



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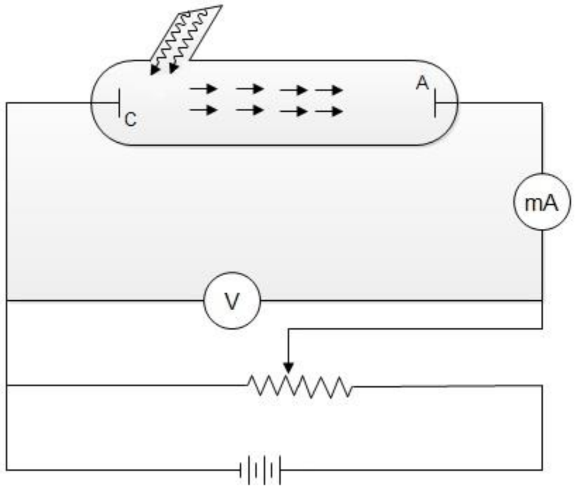
Experimental Study of Photo Electric Effect



photoelectric effect

The experimental setup consists of an evacuated glass or quartz tube with two electrodes A and C. A is a node and C are the cathodes. A constant potential difference is maintained between the cathode C and the anode A by a battery. The photoelectric current is measured by millimeter while the potential difference is measured by a voltmeter V. The tube is evacuated so that emitting surface is not contaminated by collisions with air molecules and electrons.

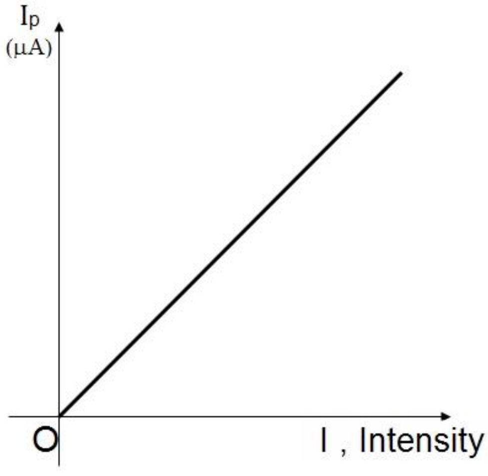
When a suitable radiation is an incident on the electrode C, electrons are emitted. These electrons get accelerated towards the plate A if it is kept at a positive potential with respect to the cathode. A current thus flows in the outer circuit which is called photo-current.

When intensity and frequency of the incident light are kept fixed while the potential of the anode is varied, it is increased in positive potential on the anode A till it reaches a value when photoelectric current reaches a saturation value. Here all the emitted electrons reach the anode A and there is no further increase in photocurrent with the increase in the positive potential of electrode A.

On the other hand, if the negative potential is applied to the plate A with respect to the cathode and is increased gradually, we find that photocurrent decreases rapidly and finally becomes zero at a certain negative potential on plate A. The minimum value of negative potential to plate A at which photoelectric current becomes zero is called stopping potential or cut off potential (V_0). In such a case, the work done by stopping potential is equal to the maximum kinetic energy of the photoelectrons emitted

i.e.$eV0=1/2mv^2max$

Effect of Intensity of Incident Light on the Photo Electric Current



verification of photoelectric current

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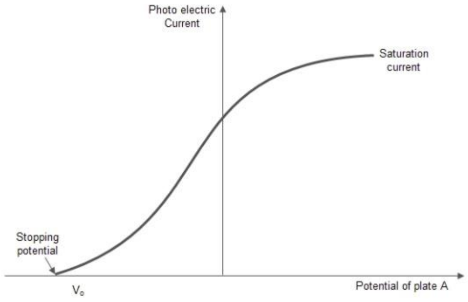
Suppose a constant potential difference be applied across the electrode A and C. When ultra-violet light is incident on the cathode C, photoelectrons are emitted which are collected by plate A.
The photoelectric current I_p constituted by these photoelectrons is measured by micro-ammeter. As the intensity of the incident light increases keeping frequency constant more photoelectrons are emitted by the electrode C and hence photoelectric current increases linearly $I_p \alpha I$. The variation of photoelectric current with the intensity of incident light is shown in the figure. Since the photoelectric current is directly proportional to the number of photoelectrons emitted per second, therefore the number of photoelectrons emitted per second is directly proportional to the intensity of incident light.

Effect of Potential on Photoelectric Current



effect of potential on photoelectric current
When the light of suitable frequency falls on the photosensitive electrode C, photoelectrons are emitted. These electrons get accelerated towards the electrode C and constitute the current called photoelectric current. For fixed frequency and incident of light, these photoelectric current increases with increase in applied positive potential of plate A. When all the photoelectrons emitted by electrode C reach the plate A, the photoelectric current attains maximum value known as saturation current. Now the potential of plate A is decreased such that it attains negative potential with respect to electrode C. The negative potential applied to plate A is increased to a certain value V_0, for which no-photo-electrons reach the plate A for which photoelectric current becomes zero is called cut-off potential or stopping potential.
At this stage, the maximum kinetic energy $1/2mv\ ^2$max of photoelectron must be equal to eV0
stopping potential is equal to the maximum kinetic energy of the photoelectrons emitted
i.e.$1/2mv^2$ max=eV0
Thus, the maximum kinetic energy of a photoelectron can be determined by the knowing the value of the stopping potential.
If the intensity of the incident light is increased and frequency is kept same then the value of photoelectric current and saturated current increase but there is no change on stopping potential.
Effect of Frequency of Incident Light on stopping Potential
The intensity of incident light is kept constant, but the frequency is changed so that in each case the saturation current is exactly the same. Now for a given frequency f_1 of the incident light, the positive potential at plate A is decreased to zero. Now, the plate A is given negative potential be V_{01}. The experiment is repeated with the incident light of frequency $f_2>f_1$. It is found that stopping potential also increases. Thus, we found that the value of stopping potential depends on upon the frequency of the incident light.
Threshold frequency
When a graph is plotted between the frequency of the incident light and the stopping potential, it is found to be a straight line as shown in the figure. It shows that there is a minimum value of frequency f_0 of the incident light below which photoelectrons emission is not possible. This frequency is known as threshold frequency or cut-off frequency f_0. The value of threshold frequency depends on the nature of the substance emitting the photo-electrons.
A photon is the smallest discrete amount of electromagnetic energy, also known as a **quantum**. It’s the fundamental unit of all light.

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Photons are continually in motion and travel at a constant speed of 2.998 x 10^8 m/s to all observers in a vacuum. The speed of light, indicated by the letter **c.** Every photon has a specific quantity of energy and momentum. The photon's energy is provided by,

E=hν

where,

- h is the Planck's constant. The value of the Planck constant is $h=6.626\times10^{-34}$ J s
- ν is the frequency of the light.

The momentum of a photon is given by,

p=h/λ

where,

- λ is the wavelength of light.
- h is the Planck's constant.

Properties of Photon

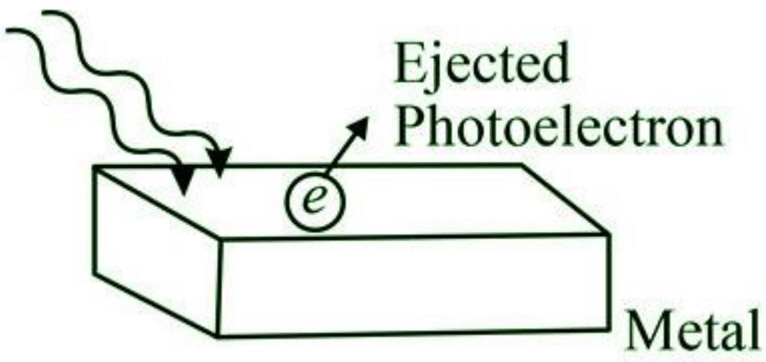
Photons have the following basic properties:

- The quantity of photons crossing an area per unit time increases as light intensity increases. It has no effect on the radiation's energy.
- Electric and magnetic fields have no effect on a photon. It has no electrical charge.
- A photon is massless.
- It's a sturdily constructed particle.
- When radiation is emitted or absorbed, photons can be generated or destroyed.
- During a photon-electron collision, the whole energy and momentum are conserved.
- A photon is incapable of decay on its own.
- A photon's energy can be transferred when it interacts with other particles.
- In contrast to electrons, which have a spin of 1/2, a photon has a spin of one. Its spin axis is perpendicular to the travel direction. The polarization of light is supported by this feature of photons.

Photoelectric Effect

When a metal is exposed to light, the photoelectric effect occurs, in which the metal emits electrons from its valence shell. The emitted electron is known as **photoelectron**, and this phenomenon is commonly known as **photoemission**.

Wilhelm Ludwig Franz Hallwachs was the first to notice the photoelectric effect, which Heinrich Rudolf Hertz later confirmed. This phenomenon, as well as the quantum nature of light, were explained by Einstein. In 1921, Einstein was awarded the Nobel Prize for Physics for his work on the Photoelectric Effect.



Threshold Energy for the Photoelectric Effect

The photons that strike the metal's surface must have enough energy to overcome the attractive forces that bind the electrons to the nuclei in order for the photoelectric effect to occur. The threshold energy (represented by the symbol Φ) is the least amount of energy required to remove an electron from a metal. A photon's frequency must be identical to the threshold frequency in order for it to have the same energy as the threshold energy (which is the minimum frequency of light required for the photoelectric effect to occur). The corresponding

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wavelength (called the threshold wavelength) is generally denoted by the sign λ_{th}, and the threshold frequency is usually denoted by the symbol ν_{th}. The following is the link between the threshold energy and the threshold frequency.

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

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

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

$h\nu = h\nu_{th} + 1/2\ m_e v^2$

where,

- E_{photon} signifies the incident photon's energy, which is equal to hν.
- Φ signifies the metal surface's threshold energy, which is equal to $h\nu_{th}$.
- $E_{electron}$ is the photoelectron's kinetic energy, which is $1/2mev^2$ (m_e = mass of electron = 9.1×10^{-31} kg).

There will be no emission of photoelectrons if the photon's energy is less than the threshold energy (since the attractive forces between the nuclei and the electrons cannot be overcome). As a result, if $\nu < \nu_{th}$, the photoelectric effect will not occur. There will be an emission of photoelectrons if the photon frequency is exactly equal to the threshold frequency ($\nu=\nu_{th}$), but their kinetic energy will be zero.

Minimum Condition for Photoelectric Effect

- **Threshold Frequency (γ_{th}):** The threshold frequency for the metal is the lowest frequency of incident light or radiation that will generate a photoelectric effect, i.e. ejection of photoelectrons from a metal surface. It is constant for one metal, but various metals may have varying values.

If γ = frequency of incident photon and γth= threshold frequency, then,

1. If $\gamma < \gamma_{th}$, there will be no photoelectron ejection and, as a result, no photoelectric effect.
2. If $\gamma=\gamma_{th}$, photoelectrons are simply expelled from the metal surface, and the electron's kinetic energy is zero.
3. If $\gamma>\gamma_{th}$, photoelectrons, and kinetic energy will be ejected from the surface.

- **Threshold Wavelength (λ_{th}):** The metal surface with the largest wavelength to incident light is known as the threshold wavelength during electron emission.

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

For λ = wavelength of the incident photon, then

1. If $\lambda<\lambda_{th}$, the photoelectric effect will occur, and the expelled electron will have kinetic energy.
2. If $\lambda= \lambda_{th}$, the photoelectric effect will be the only one that occurs, and the kinetic energy of the ejected photoelectron will be zero.
3. There will be no photoelectric effect if $\lambda>\lambda_{th}$.

- **Work Function or Threshold Energy (Φ):** The work function/threshold energy is the minimum amount of thermodynamic work required to remove an electron from a conductor to a location in the vacuum just outside the conductor's surface.

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

If E = energy of an incident photon, then

1. If E<Φ, there will be no photoelectric effect.
2. If E =Φ, just the photoelectric effect occurs, but the kinetic energy of the expelled photoelectron is 0.
3. If E > photoelectron, photoelectron will be zero.
4. If E >Φ, the photoelectric effect will occur, as will the expelled electron's possession of the kinetic energy.

Principle of Photoelectric Effect: A metal surface is irradiated with light in the photoelectric effect, and when light falls on the metal's surface, photoemission occurs, and photoelectrons are ejected from the metal's surface. The energy of the wave's photon is transmitted to the metal atom's electrons, which causes the electrons to get excited and expelled with a certain velocity.

Equation of Photoelectric Effect

The photon's energy is equal to the sum of the metal's threshold energy and the photoelectron's kinetic energy.

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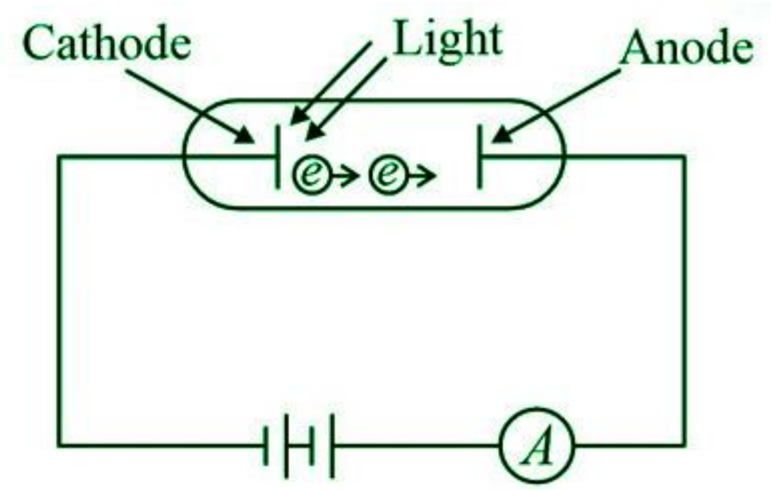


Thus, the equation of photoelectric wave is given by,

$KE_{max}=hv-\phi$

where,

- KE_{max} is the maximum kinetic energy of the photoelectron
- hv is the energy of the photon.
- φ is the work function of the metal

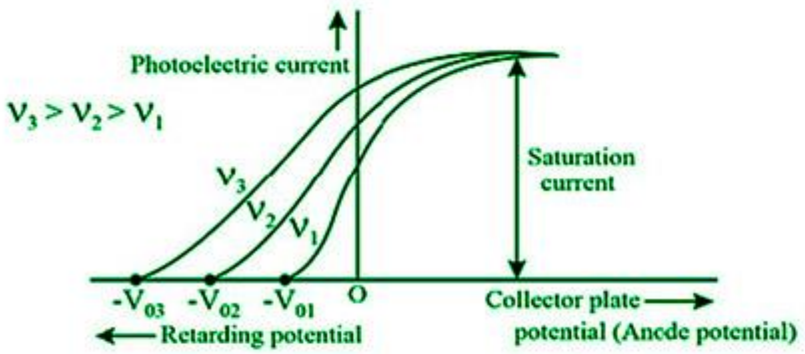
Work function is determined by the metal in question, and it will change if the metal is changed. The work function is sometimes defined in terms of threshold frequency, which is the frequency of light for which the emitted Photoelectron's maximal kinetic energy is zero.

$\phi=hv_0$

where,

- v_0 is the threshold frequency.
- h is the Planck's constant.

The maximum kinetic energy remains constant as the light intensity increases, but the value of photocurrent increases.



Characteristics Of Photoelectric Effect

- The threshold frequency varies by material; different materials have varying threshold frequencies.
- The photoelectric current is proportional to the intensity of light.
- The photoelectrons' kinetic energy is related to the frequency of light.
- The frequency is directly proportional to the stopping potential, and the process is immediate.

Factors affecting Photoelectric Effect

The photoelectric effect depends on :

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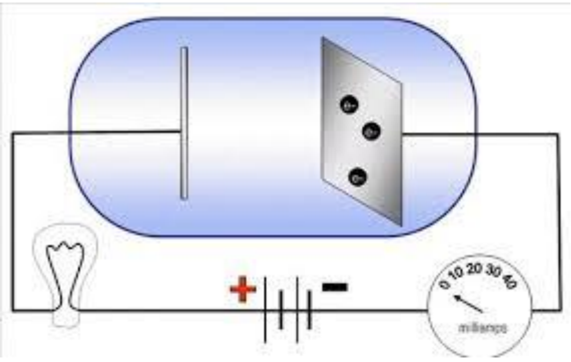
1. The intensity of incident radiation.
2. A potential difference between metal plate and collector.
3. Frequency of incident radiation.

Applications of Photoelectric Effect

- Solar Panels use it to generate power. Metal combinations in these panels allow power to be generated from a wide variety of wavelengths.
- **Sensors for motion and position:** A photoelectric material is placed in front of a UV or IR LED in this case. Light is switched off when an object is placed between the LED and the sensor, and the electronic circuit recognizes a change in potential difference.
- Lighting sensors, such as those found in smartphones, allow for automatic screen brightness adjustment in response to ambient light. This is due to the fact that the quantity currently created by the photoelectric effect is proportional to the amount of light that strikes the sensor.
- Digital cameras can detect and record light because they have photoelectric sensors that respond to different colours of light.
- **X-Ray Photoelectron Spectroscopy (XPS):** This approach involves irradiating a surface with x-rays and measuring the kinetic energy of the electrons that are released. Important features of a surface's chemistry, such as elemental composition, chemical composition, the empirical formula of compounds, and chemical state, can be acquired.
- In burglar alarms, photoelectric cells are utilized.
- Photomultipliers use it to detect low light levels.
- In the early days of television, it was used in video camera tubes.
- This phenomenon is used in night vision systems.

The photoelectric effect is also useful in the research of nuclear reactions. Because released electrons tend to carry specific energy that is distinctive of the atomic

Practical Application:



Photoelectric cell

Photoelectric cells were originally used to detect light, using a vacuum tube containing a cathode, to emit electrons, and an anode, to gather the resulting current. Today, these "phototubes" have advanced to semiconductor-based photodiodes that are used in applications such as solar cells and fiber optics telecommunications.

Photomultiplier tubes are a variation of the phototube, but they have several metal plates called dynodes. Electrons are released after light strikes the cathodes. The electrons then fall onto the first dynode, which releases more electrons that fall on the second dynode, then on to the third, fourth, and so forth. Each dynode amplifies the current; after about 10 dynodes, the current is strong enough for the photomultipliers to detect even single photons. Examples of this are used in spectroscopy (which breaks apart light into different wavelengths to learn more about the chemical compositions of star, for example), and computerized axial tomography (CAT) scans that examine the body.

Other applications of photodiodes and photomultipliers include:

- imaging technology, including (older) television camera tubes or image intensifiers;
- studying nuclear processes;

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- chemically analyzing materials based on their emitted electrons;
- giving theoretical information about how electrons in atoms transition between different energy states.

But perhaps the most important application of the photoelectric effect was setting off the quantum revolution, according to
Scientific American. It led physicists to think about the nature of light and the structure of atoms in an entirely new way.

Conclusion: When a metal is exposed to light, the photoelectric effect occurs, in which the metal emits electrons from its valence shell. The emitted electron is known as **photoelectron**, and this phenomenon is commonly known as **photoemission**.

Photoelectric cells were originally used to detect light, using a vacuum tube containing a cathode, to emit electrons, and an anode, to gather the resulting current. Today, these "phototubes" have advanced to semiconductor-based photodiodes that are used in applications such as solar cells and fiber optics telecommunications

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