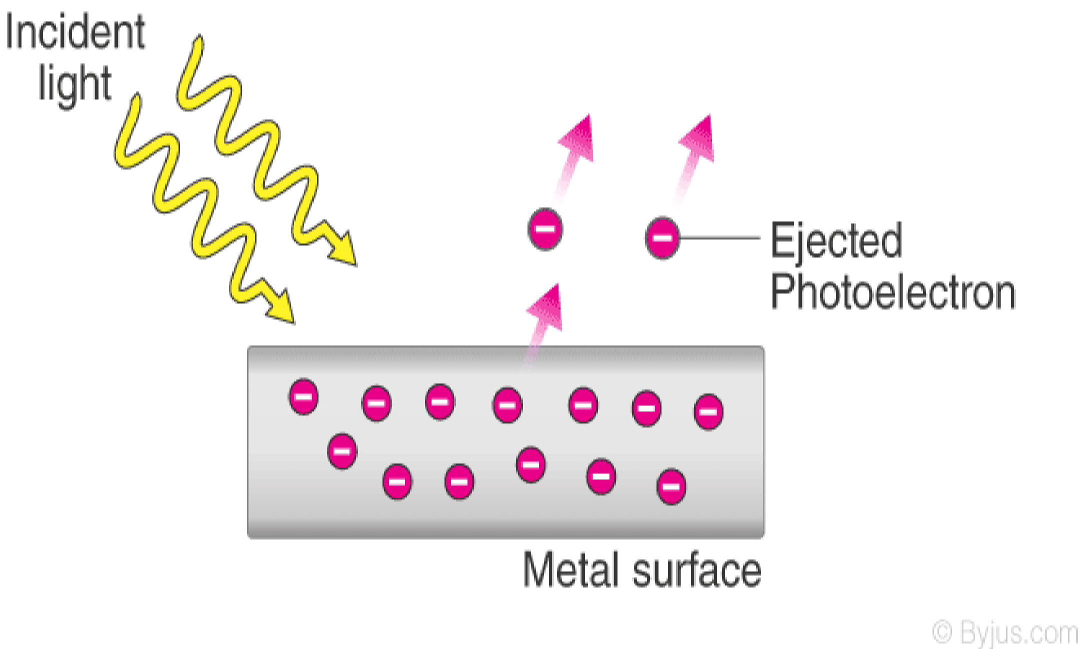
The photo-electric effect

The photoelectric effect is a phenomenon in which electrons are ejected from the surface of a metal when light is incident on it. These ejected electrons are called **photoelectrons**. It is important to note that the emission of photoelectrons and the kinetic energy of the ejected photoelectrons is dependent on the frequency of the light that is incident on the metal's surface. The process through which photoelectrons are ejected from the surface of the metal due to the action of light is commonly referred to as **photoemission**.

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. An illustration detailing the emission of photoelectrons as a result of the photoelectric effect is provided below.



Explaining the Photoelectric Effect: The Concept of Photons

The photoelectric effect cannot be explained by considering light as a wave. However, this phenomenon can be explained by the particle nature of light, in which light can be visualized as a stream of particles of electromagnetic energy. These ‘particles’ of light are called **photons**. The energy held by a photon is related to the frequency of the light

Planck’s equation:

$$\mathbf{E = h\nu}$$

$$\boldsymbol{\nu = c / \lambda}$$

Where,

- **E** the energy of the photon
- **h** is Planck’s constant
- $\boldsymbol{\nu}$ 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.

Examples

1. Ultraviolet radiation has a frequency of 6.8×10^{15} Hz. Calculate the energy, in joules, of the photon.

2. Find the energy, in joules per photon, of microwave radiation with a frequency of 7.91×10^{10} Hz.

3. A sodium vapor lamp emits light photons with a wavelength of 5.89×10^{-7} m. What is the energy of these photons?

4. One of the electron transitions in a hydrogen atom produces infrared light with a wavelength of 746.4 nm. What amount of energy causes this transition?

5. Find the energy in kJ for an x-ray photon with a frequency of 2.4×10^{18} s^{-1} .

6. A ruby laser produces red light that has a wavelength of 500 nm. Calculate its energy in joules.

7. What is the frequency of UV light that has an energy of 2.39×10^{-18} J?

8. What is the wavelength and frequency of photons with an energy of 1.4×10^{-21} J?

9. What is the energy of a light that has 434 nm?

10. What is the wavelength of a light that has a frequency of $3.42 \text{ x } 10^{11}$ Hz?

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.

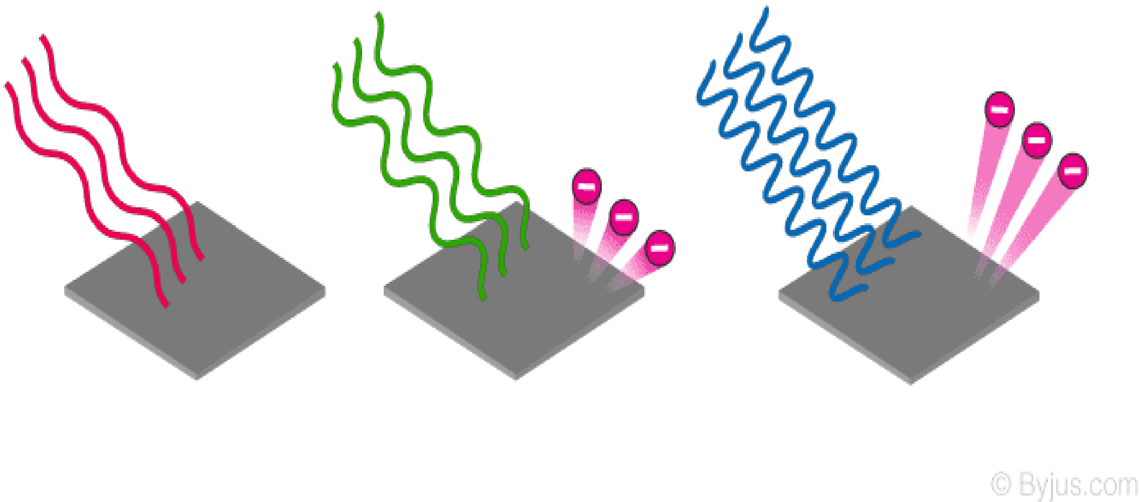
$$\mathbf{E_{photon} = \Phi + E_{electron}}$$

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

Where,

- E_{photon} the energy of the incident photon, which is equal to $h\nu$
- Φ the threshold energy of the metal surface, which is equal to $h\nu_{th}$
- $E_{electron}$ the kinetic energy of the photoelectron, which is equal to $\frac{1}{2}m_e v^2$ (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.



Properties of the Photon

- For a photon, all the quantum numbers are zero.
- A photon does not have any mass, 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 matters 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.
- The momentum and energy of the photons are related as given below

E = p.c where

p = magnitude of the momentum

c = speed of light.

Definition of Photoelectric Effect

The phenomenon of metals releasing electrons when they are exposed to the light of the appropriate frequency is called photoelectric effect, and the electrons emitted during the process are called photoelectrons.

Principle of Photoelectric Effect

The law of conservation of energy forms the basis for the photoelectric effect.

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

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: $1/2\ mv^2$.

Characteristics Of Photoelectric Effect

- The threshold frequency varies with material, it is different for different materials.
- The photoelectric current is directly proportional to the light intensity.
- The kinetic energy of the photoelectrons is directly proportional to the light frequency.
- The stopping potential is directly proportional to the frequency and the process is instantaneous.

Factors affecting Photoelectric Effect

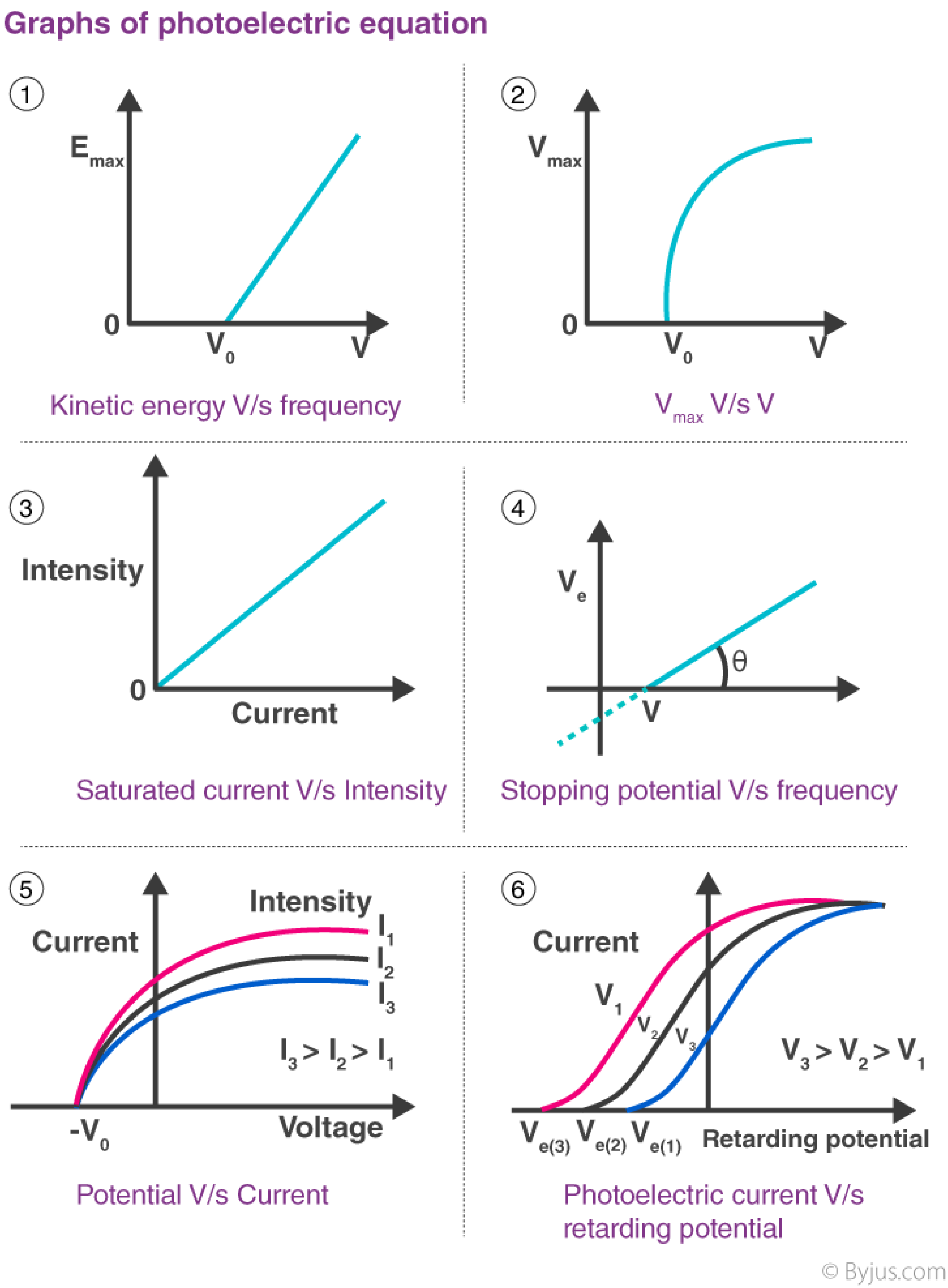
With the help of this apparatus, we will now study the dependence of the photoelectric effect on the following factors.

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

3. Frequency of incident radiation.

Different Graphs of Photoelectric Equation

- Kinetic energy V/s frequency
- V_{max} V/s v
- Saturated Current V/s Intensity
- Stopping potential V/s frequency
- Potential V/s current: (γ = constant)
- Photoelectric current V/s Retarding potential


Graphs of photoelectric equation
1
E_{max}
0
V_0
V
Kinetic energy V/s frequency
2
V_{max}
0
V_0
V
V_{max} V/s V
3
Intensity
0
Current
Saturated current V/s Intensity
4
V_e
θ
V
Stopping potential V/s frequency
5
Current
Intensity
I_1
I_2
I_3
$I_3 > I_2 > I_1$
$-V_0$
Voltage
Potential V/s Current
6
Current
V_1
V_2
V_3
$V_3 > V_2 > V_1$
$V_{e(3)}$ $V_{e(2)}$ $V_{e(1)}$
Retarding potential
Photoelectric current V/s retarding potential
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Applications of Photoelectric Effect

- Used to generate electricity in Solar Panels. These panels contain metal combinations that allow electricity generation from a wide range of wavelengths.
- **Motion and Position Sensors:** In this case, a photoelectric material is placed in front of a UV or IR LED. When an object is placed in between the Light-emitting diode (LED) and sensor, light is cut off and the electronic circuit registers a change in potential difference
- Lighting sensors such as the ones used in smartphones enable automatic adjustment of screen brightness according to the lighting. This is because the amount of current generated via the photoelectric effect is dependent on the intensity of light hitting 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 technique uses x-rays to irradiate a surface and measure the kinetic energies of the emitted electrons. Important aspects of the chemistry of a surface can be obtained such as elemental composition, chemical composition, the empirical formula of compounds and chemical state.
- Photoelectric cells are used in burglar alarms.
- Used in photomultipliers to detect low levels of light.
- Used in video camera tubes in the early days of television.
- Night vision devices are based on this effect.
- The photoelectric effect also contributes to the study of certain nuclear processes. It takes part in the chemical analysis of materials since emitted electrons tend to carry specific energy that is characteristic of the atomic source.

Problems on Photoelectric Effect

1. In a photoelectric effect experiment, the threshold wavelength of incident light is 260 nm and E (in eV) = 1237/λ (nm). Find the maximum kinetic energy of emitted electrons.

Solution:

$K_{max} = hc/\lambda - hc/\lambda_0 = hc \times [(\lambda 0 - \lambda)/\lambda\lambda 0]$

$\Rightarrow K_{max} = (1237) \times [(380 - 260)/380\times 260] = 1.5$ eV

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

What are the conditions for the photoelectric effect?

The minimum condition required for the emission of electrons from the outermost shell of an atom is that the frequency of incident rays should be very high. This will provide energy to the electron to leave its outermost shell.

What is the importance of the photoelectric effect?

The study of the photoelectric effect has led to expanding our understanding of the quantum nature of light and electrons. It has further influenced the formation of the concept of wave-particle duality. The photoelectric effect is also widely used to investigate electron energy levels in the matter.

Which popular device is based on the photoelectric effect?

One of the common devices based on this effect is the photoelectric cell or photodiode.