QUANTUM PHYSICS

Quantum physics studies matter and energy at the subatomic and atomic levels. It attempts to explain the properties of atoms and molecules and their fundamental particles like protons, neutrons, electrons, gluons, and quarks. The properties of particles include their interactions with each other and with energy.

QUANTUM THEORY OF RADIATION

It was introduced by Max Planck and Albert Einstein It explains how energy is emitted and absorbed in discrete packets (quanta), the key points of the Quantum theory of radiation are:

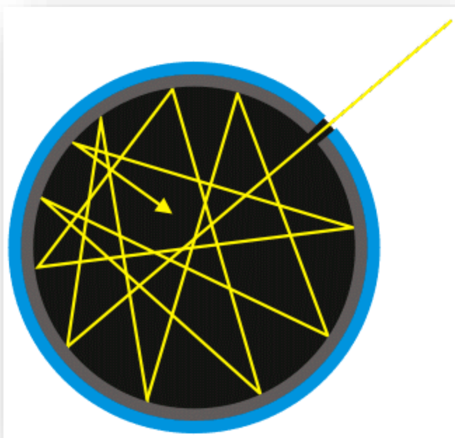
1. Continuous radiation or emission of energy is not possible. Quanta, the term for the discrete packets of energy it emits, are the smallest units of its radiation.
2. A photon is the unit of measurement for a particle of radiation when it is in the form of light. In the case of light, photons are tiny energy particles.
3. The frequency of the radiation is exactly proportional to the energy of a photon or quantum of energy. Where h denotes Planck's constant and **ν** denotes radiation frequency, $E = h\nu$.
4. There are a lot of ways to express the total energy of radiation, including $h\nu$, $2h\nu$, and so on.

BLACK BODY

An object that can absorb all the radiation falling on it is called a black body. Just as a black body is a perfect absorber, so is the perfect emitter when heated.

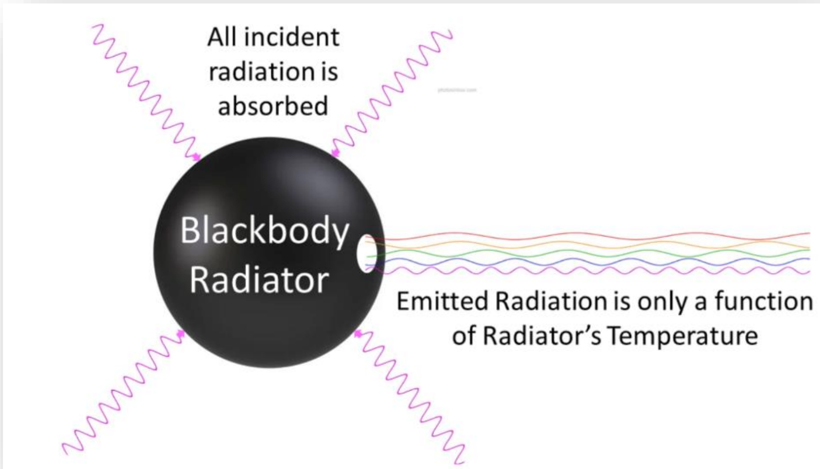
CONSTRUCTION

We can make such an ideal radiator by forming a cavity within a block, the walls of which are blackened by lamp back. A small hole is pierced through the walls of the cavity so that a sample of the radiation can escape into the laboratory to be examined. Any radiation entering the hole of the cavity is trapped by multiple reflections and very little of it is able to escape. Therefore, this *hole in a cavity radiator behaves like a black body*.



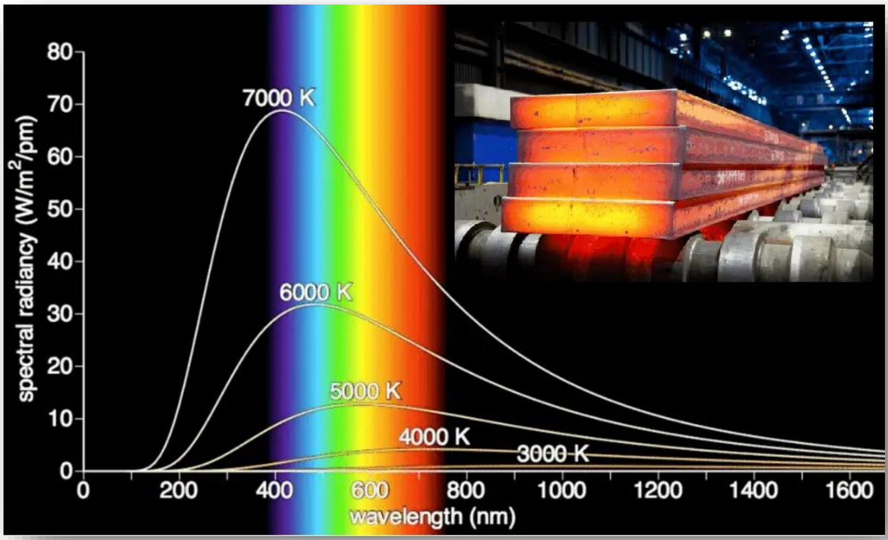
BLACK BODY RADIATION

A black body is an idealized object that absorbs all incident radiation and also emits it in a continuous spectrum of colors, depending upon its temperature as shown in the figure.



SOME EXPERIMENTAL FACTS ABOUT BLACKBODY RADIATIONS:

- The blackbody spectrum depends only on the temperature of the object, and not on what it is made of i.e., material. An iron horseshoe, a ceramic vase, and a piece of charcoal --- all emit the same
- blackbody spectrum if their temperatures are the same. As the temperature of an object increases, it emits more intense blackbody radiations of all wavelengths.
- As the temperature of an object increases, the peak wavelength of the blackbody spectrum curve shifts towards a shorter wavelength (Blue-shift). For example, blue stars are hotter than red stars.
- The blackbody spectrum peak shift always becomes small at the left-hand side i.e., the short wavelength, high frequency.



CLASSICAL EXPLANATION OF BLACK BODY RADIATION:

WEIN'S DISPLACEMENT LAW

Wien's displacement law states that the wavelength at which the intensity of blackbody radiation is maximum is inversely proportional to the temperature of the blackbody. As the temperature increases, the peak of the blackbody radiation curve shifts to shorter wavelengths. This relationship is mathematically expressed as:

$$\lambda_{max} \ \alpha \ \frac{1}{T}$$

$$\lambda_{max} \ T = \ constant$$

$$\lambda_{max} \ T = \ 2.898 \times 10^{-3} \, m \, K$$

where λ_{max} is the wavelength at which the curve peaks and **T** is the absolute temperature of the object emitting radiation

The second effect is that the total amount of energy the object emits increases with temperature.

THE STEFAN-BOLTZMANN LAW

"The amount of energy of all wavelengths radiated per second per unit area of the black body is proportional to the fourth power of absolute temperature".

$$E \ \alpha \ T^4$$

$$E = \sigma T^4$$

Where $\sigma = 5.670 \times 10^{-8}$ W/m^2. K^4 is called the Stefan-Boltzmann constant.

THE RAYLEIGH-JEAN LAW

This Law states that the energy per unit volume per unit wavelength of blackbody radiation is inversely proportional to the fourth power of the wavelength (λ),
The law is given by the formula:

$$E_{(\lambda,T)} = \frac{2\,c\,k\,T}{\lambda^4}$$

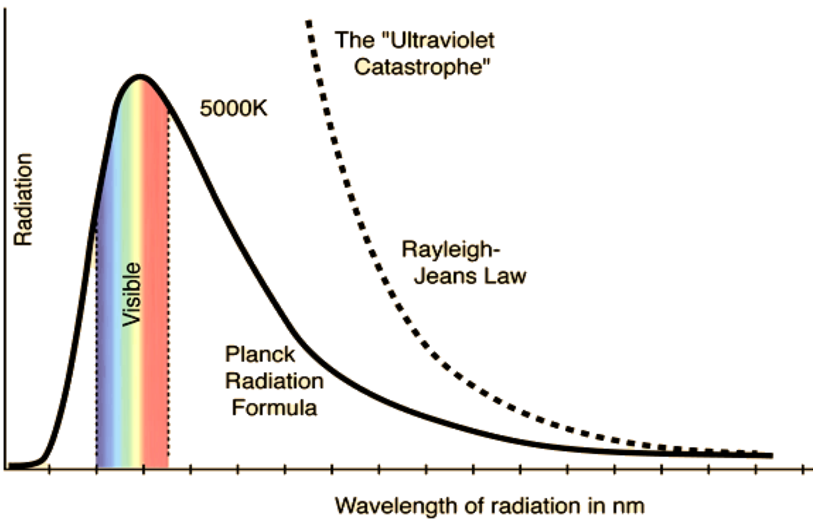
Mathematically expressed as:

$$E_{(\lambda,T)} = \frac{constant}{\lambda^4}$$

$$E_{(\lambda,T)} \;\alpha\; \frac{1}{\lambda^4}$$

MISMATCH OF THEORY AND EXPERIMENT DATA

An experimental plot of the black body radiation spectrum is shown in the right figure, together with the theoretical prediction of the Rayleigh-Jean law. At longer wavelengths, the Rayleigh–Jean law is in reasonable agreement with the experimental data, but at shorter wavelengths major disagreement is apparent, We can understand the disagreement by noting that as λ_{max} approaches zero, the approaches infinity. In contrast to this prediction, the experimental data plotted in the figure shows that as λ approaches zero, intensity also approaches zero. This mismatch of theory and experiment was so disconcerting that scientists called it the ***ultraviolet catastrophe.***



PLANCK'S RADIATION LAW

To overcome the difficulties in providing a successful explanation of black body curves. Planck proposed a law in 1900. In his theory, Planck made two bold and controversial assumptions concerning the nature of the oscillating at the surface of the black body :

1. The molecules can have only a discrete value of energy E_n, given by

   $$E_n = n\,hf$$

   Where n is a positive integer called a quantum number and f is the natural frequency of the oscillator of the molecules.
2. The molecules emits or absorb energy in discrete packet that later came to be called photons. The molecules emit or absorb these photons by jumping from one quantum state to another. This law created a revolution in modern physics. It agreed very well with experimental and theoretical curves for black body radiation.

PARTICLE NATURE OF ELECTROMAGNETIC RADIATION:

Electromagnetic radiation can be described in terms of a stream of **mass-less particles, called photons.** Each photon contains a certain amount of energy. The different types of radiation are defined by the amount of energy found in the photons.

THE PHOTON

DEFINITION

Discrete packets (amounts) of electromagnetic energy are called photons or quanta. These are the carriers of electromagnetic forces.

CHARACTERISTICS

The following are the important characteristics of photons.

1- ***CHARGE***

A photon has no charge. It can interact with all charged and some neutral particles.

2- ***STABILITY***

It is a very stable particle with infinite lifetime until it interacts with other particles**.**

3- ***ENERGY***

The energy of a photon is given by: $E = h\nu$

where υ = frequency and h (Planck's constant) $= 6.626 \times 10^{-23}$ J s

4- ***SPEED***

Photons may have different energies but they always move with of speed of light $c = 3 \times 10^8$ m/s.

5- ***MASS***

The rest mass of a photon is zero i.e., it is a mass-less particle. It exists due to its motion.

$$E = mc^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(i)}$$

where 'c' is the speed of light

$$E = h\nu \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(ii)}$$

comparing equation (i) and (ii)

$$mc^2 = h\nu$$

$$m = \frac{h\nu}{c^2}$$

it is clear from the above equation that 'm' approaches zero as c^2 is very large quantity.

6- *MOMENTUM*

The Einstein's famous formula mathematically relates the concept of energy and mass

$$E = mc^2 \ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

and $$E = h\nu \ldots\ldots\ldots\ldots\ldots\text{(ii)}$$

comparing equation (i) and (ii)

$$mc^2 = h\nu$$

$$(mc)c = h\nu$$

Where p = mc is the momentum of the photon.

$$(P)c = h\nu$$

$$P = \frac{h\nu}{c}$$

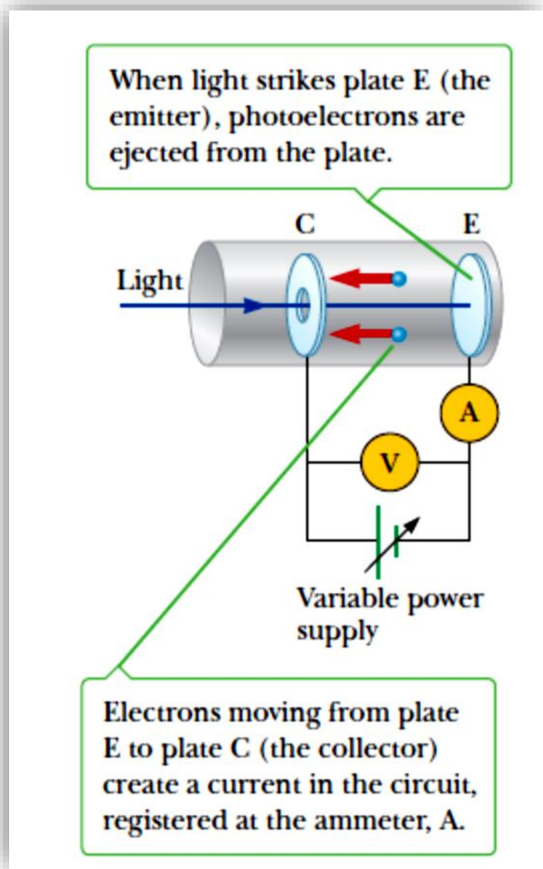
THE PHOTOELECTRIC EFFECT

DEFINITION

When electromagnetic radiation like the light of a certain frequency is shined on metallic materials; electrons are emitted due to the absorption of light by the electrons on the surface of the material is called the photoelectric effect. Electrons emitted are called photoelectrons and the current due to these electrons is called photocurrent.

DEMONSTRATION

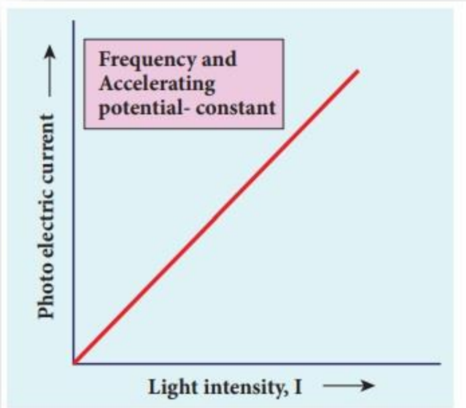
Consider an evacuated quartz tube that contains a metallic plate E connected to the negative terminal of a battery and another plate C that is connected to the positive terminal of the battery. When the tube is kept is the dark, the galvanometer shows no deflection. Light from the source is allowed to fall on plate E the galvanometer indicates deflection. When the light is switched off, the current stops.



FOLLOWING OBSERVATIONS WERE MADE DURING THIS EXPERIMENT:

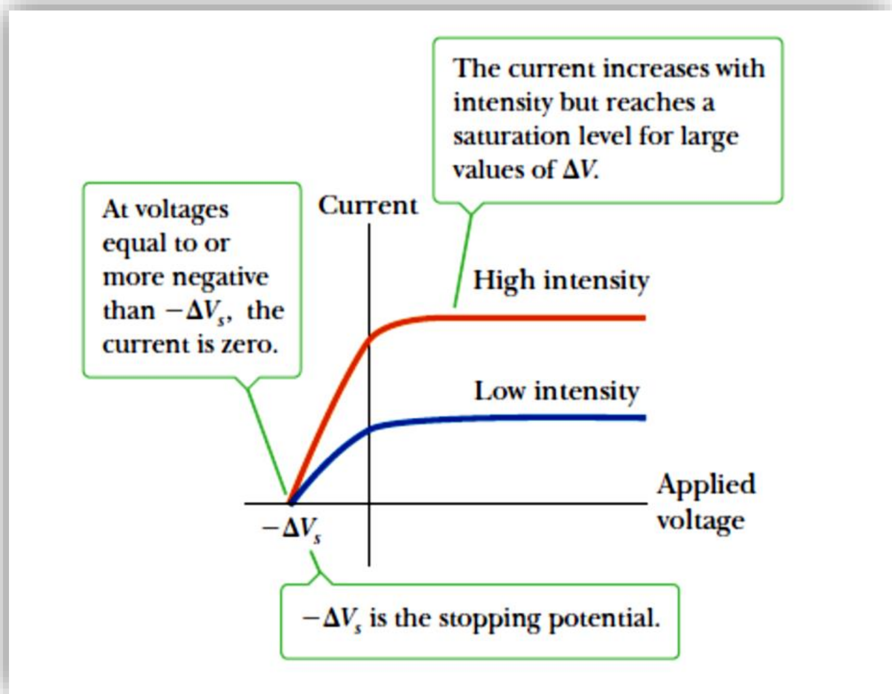
1. INTENSITY OF RADIATION

For a constant potential difference between the cathode and anode, the number of electrons emitted from the cathode increases with increasing intensity of radiation.



2 STOPPING POTENTIAL

For a constant intensity and frequency of incident radiation the photoelectric current varies with the potential difference V between the cathode and anode and reaches a constant value beyond which further increase of potential difference does not affect the photoelectric current, instead, if the anode is made more and more negative with respect of the photo- cathode surface the current decreases. This negative potential (for the cathode) of the plate is called retarding potential. As shown in Fig:



For a particular value of retarding potential, the photoelectric current becomes zero.

This potential is called cut-off or stopping potential V_o and is a measure of the maximum kinetic energy of photo-electrons, we can write

$$K.E_{max} = e\,V_o$$

where $K.E_{max}$ (the maximum kinetic energy of the ejected electron.)

3. ***THE STOPPING POTENTIAL AND HENCE THE MAXIMUM KINETIC ENERGY***

The stopping potential and hence the maximum kinetic energy $K.E_{max}$ of photo-electrons is independent of the intensity of incident radiation and depends only on the frequency ν of radiation.

4 ***THRESHOLD FREQUENCY***

The minimum frequency of incident light required to eject electrons from the metal surface without any K.E is called threshold frequency ν_o It depends upon the nature of the metal surface and the corresponding wavelength 1s called Threshold Wavelength λ_0, $\left(\lambda_0 = \frac{hc}{\Phi_0}\right)$

5- **WORK FUNCTION**

The minimum energy required to eject an electron from metal surface i.e., to overcome the binding force of the nucleus is called the work function Φ_0. This is also called energy corresponding to threshold frequency.

$$\boldsymbol{\Phi_0 = h\,\nu_0}$$

THE FAILURE OF CLASSICAL WAVE THEORY OF LIGHT

These major features of the photoelectric effect cannot be explained in terms of classical wave theory.

1- According to wave theory, the photoelectric effect should occur for any frequency of the light, because electrons may come out by absorbing enough energy from incident light.

2- The velocity and hence the K_{max} of photoelectrons should depend upon the amplitude i.e., the intensity of the light beam rather than the frequency.

3- For weak light intensity, classical physics expects the photoelectrons to acquire some time to absorb the incident radiation before they gain enough kinetic energy to escape from the metal.

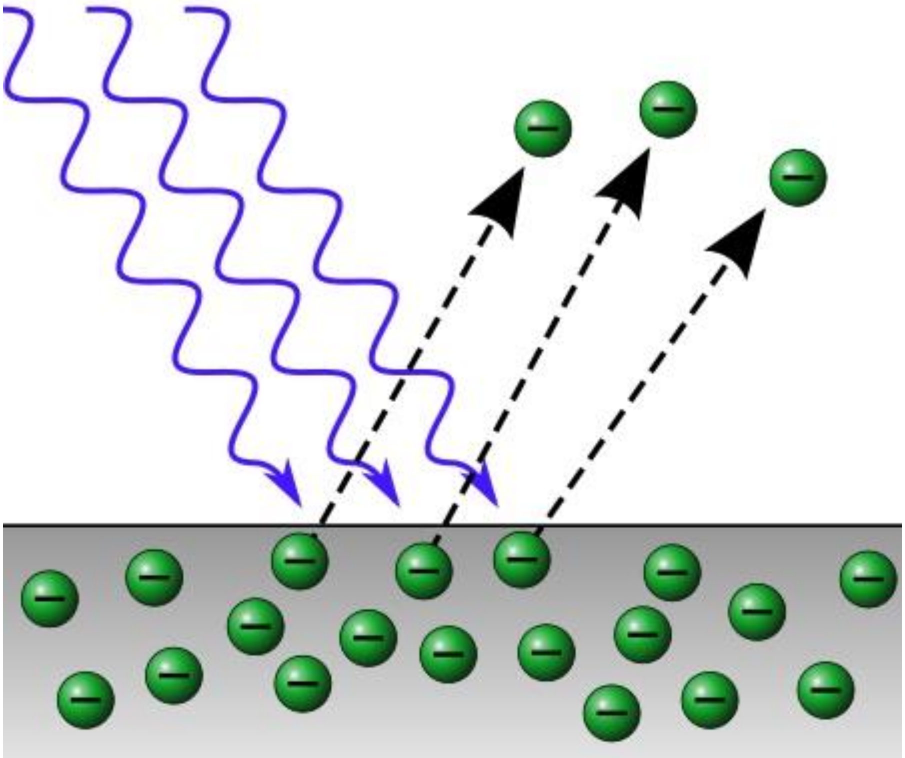
EINSTEIN'S EXPLANATION ON THE BASIS OF QUANTUM THEORY

In 1905 Einstein proposed that a light beam behaves like a stream of particles, with its energy concentrated into bundles, later called photons. The energy of a single photon is given by

$$\boldsymbol{E = h\nu},$$

where $\boldsymbol{\nu}$ is the frequency of light.

According to Einstein, a single photon carries an energy hv into metal where a single electron absorbs it. Part of this energy is used in ejecting an electron from the metal surface. The excess energy $(hv - \Phi)$ becomes the electron kinetic energy.

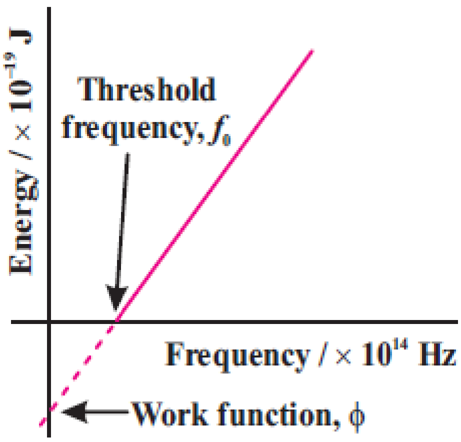


(Incident energy) = (work function) + (K.E of electrons)

$$hv = \Phi_0 + k_{max}$$

$$hv = \Phi_0 + \frac{1}{2} m v^2$$

So, the work function Φ_0 is the minimum energy that must be supplied to the electron for it to leave the Metal surface. As shown in the figure



Now

$$hv = \Phi_0 + e V_0$$

$$h\nu = h\nu_0 + e V_0$$

$$h\nu - h\nu_0 = e V_0$$

$$h\frac{c}{\lambda} - h\nu_0 = e V_0$$

$$e V_0 = h\frac{c}{\lambda} - h\nu_0$$

These are called Einstein's photoelectric equations

PHOTOELECTRIC EFFECT IN SOLAR CELLS AND PHOTOCELLS:

A solar cell produces an electric circuit when light falls on them. They are made of two layers of semiconductor materials like silicon. One is positively charged, while the other is negatively charged. When photons from light strike the solar cell, electrons are knocked loose from the atoms in the semiconductor material. The movement of electrons generates the DC electric current

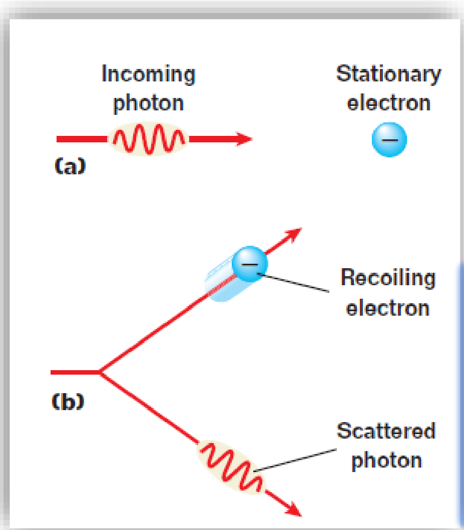
- Photocell, a device that uses the photoelectric effect to generate or control a current.
- Photovoltaic cells and photoconductive cells are examples of photoelectric cells.
- Solar cell, a device that converts electromagnetic energy into electrical energy.

THE COMPTON EFFECT QUALITATIVELY

Arthur H. Compton discovered in 1923 that the wavelengths of x rays change after they are **scattered from electrons.**

DEFINITION

The phenomenon in which a photon of wavelength λ_1 is scattered by an electron and the scattered photon has a wavelength λ_2 greater than λ_1 is called Compton effect.



(a) when the Photon collide with an electron

(b) The scattered photon has less energy and a longer wavelength than the incoming Photon

INITIAL INTERACTION:

A photon, which is a packet of electromagnetic energy, interacts with an electron in a material, typically a target like a metal or graphite.

SCATTERED PROCESS

During the interaction, the photon transfers some of its energy and momentum to the electron. This transfer causes the photon to change its direction and wavelength (or equivalently, its frequency).

CHANGE IN PHOTON ENERGY

The scattered photon energy with less energy (longer wavelength) than the initial incident photon. The amount of energy lost by the photon is directly related to the energy and momentum gain by the electron.

QUANTUM NATURE:

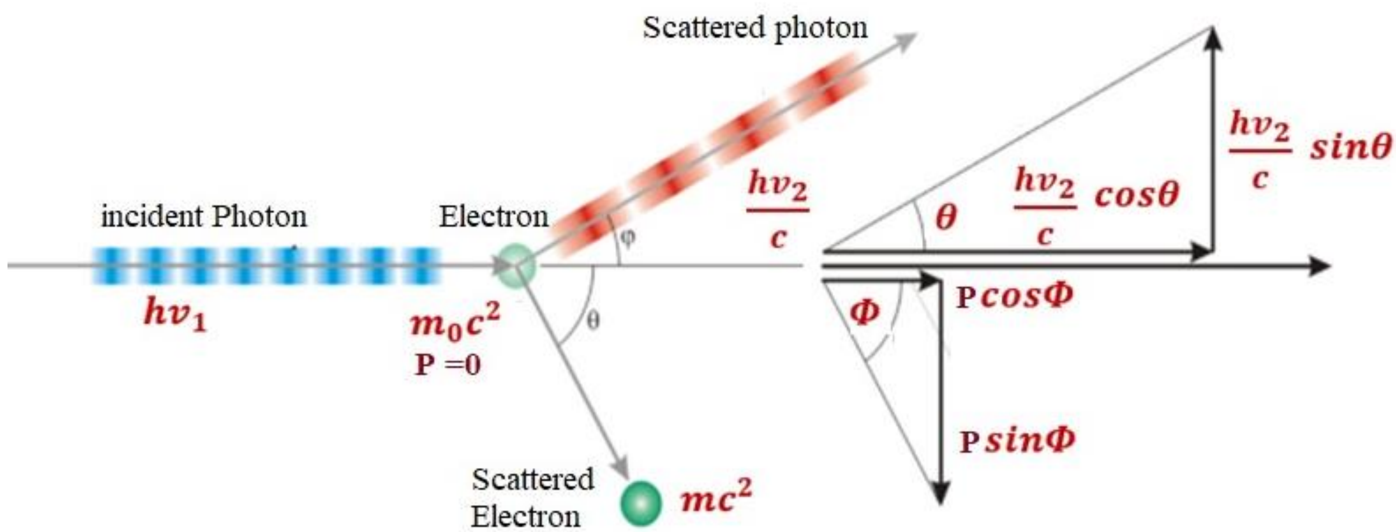
Compton's Effect cannot be explained using classical wave theory alone. Classical wave theory predicts that light should scatter uniformly without a change in wavelength. However, Compton's observations demonstrated that the scattered light has a shifted wavelength, indicating a particle-like interaction.

EXPERIMENTAL CONFIRMATION:

Compton conducted experiments where X-rays were targeted at graphite and the scattered X-rays were observed. By measuring the scattering angle and change in wavelength, he confirmed that the results were consistent with the predictions of quantum theory.

MATHEMATICAL EXPRESSION

1- CONSERVATION OF ENERGY



$$Total\ energy\ before\ Collision = Total\ energy\ after\ Collision$$

$$\binom{\text{Photon's initial}}{\text{energy}} + \binom{\text{rest mass enrgy}}{\text{of electron}} = \binom{\text{ScatteredPhoton's}}{\text{energy}} + \binom{\text{Scattered elctron's}}{\text{energy}}$$

$$h\nu_1 + m_oc^2 = h\nu_2 + mc^2 \text{ ....(i)}$$

2- CONSERVATION OF MOMENTUM (ALONG X-AXIS)

Total momentum before Collision = total momentum after Collision

Photon's momentum+ electron's momentum = Photon's momentum+ Electron's momentum

$$\frac{h\nu_1}{c} + 0 = \frac{h\nu_2}{c}\cos\theta + mv\cos\phi$$

$$\frac{h\nu_1}{c} = \frac{h\nu_2}{c}\cos\theta + mv\cos\phi \text{ ----- (ii)}$$

3- CONSERVATION OF MOMENTUM (Along y-axis)

Total momentum before Collision (Along y-axis) = total momentum after Collision(Along y-axis)

$$0 + 0 = P_2\sin\theta + (-P\cos\phi)$$

$$0 = \frac{h\nu_2}{c}\sin\theta - mv\sin\Phi \text{------(3)}$$

Solving equations (1), (2) and (3), we get

$$\frac{1}{v_1} - \frac{1}{v_2} = \frac{h}{m_o c^2}(1 - Cos\theta)$$

Similarly, $\frac{1}{v_2} = \frac{\lambda_2}{c}$ $\frac{1}{v_1} = \frac{\lambda_1}{c}$

$$\frac{\lambda_2}{c} - \frac{\lambda_1}{c} = \frac{h}{m_o c^2}(1 - Cos\theta)$$

$$\lambda_2 - \lambda_1 = \frac{h}{m_o C}(1 - Cos\theta)$$

It is clear from this equation that, Compton shift $\Delta\lambda$ depends only upon scattering angle 'θ' of photon.

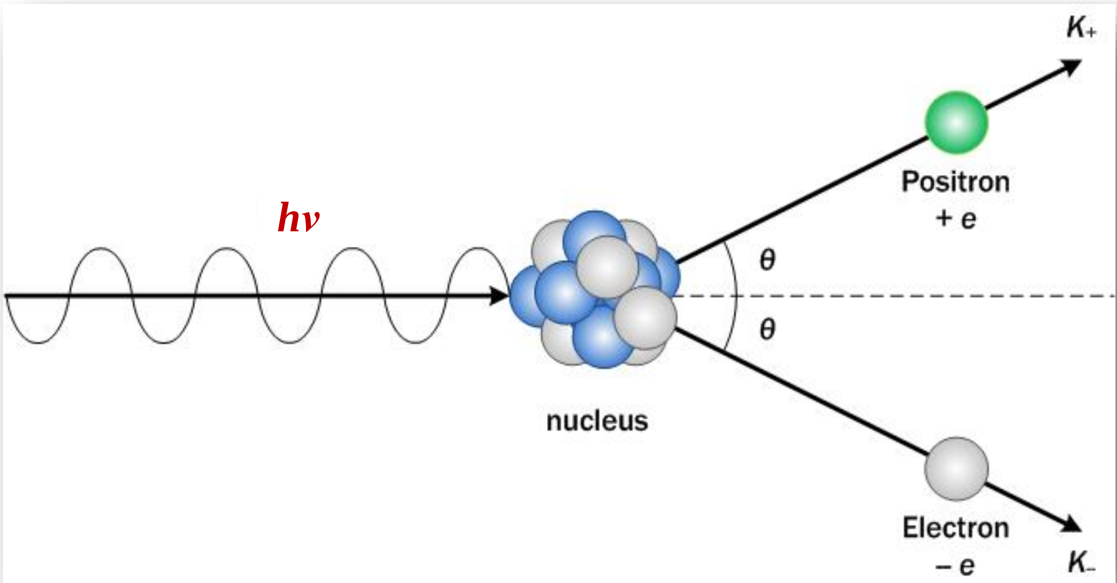
PAIR PRODUCTION

DEFINITION

A phenomenon in which a photon passes very close to a heavy, stable nucleus and disappears producing a particle antiparticle pair, is called pair production.

INTERACTION DIAGRAM

When a photon passes in the vicinity of a nucleus, it disintegrates and a pair of electron positron is created. Positron is also called *Antielectron.* This process is also called materialization of energy in conformity with the mass-energy equivalence.



CONSERVATION LAW OF PAIR PRODEUCT

For pair production to occur, a photon must have a minimum energy of 1.022 MeV. This requirement arises because the rest mass of both an electron and a positron is 0.511 MeV each. Therefore, the combined energy needed to create an electron-positron pair is $(0.511 MeV \times 2) = (1.022\text{ MeV})$; If the incident photon possesses energy exceeding 1.022 MeV, the surplus energy is distributed as kinetic energy between the electron and the positron. Therefore, the pair production reaction is given as under:

$$\gamma \rightarrow e^{+} + e^{-} = 1.02\ MeV$$

FACTS OF PAIR PRODUCTION PROCESS ARE:

This process obeys following conservation laws:

1- **CONSERVATION OF CHARGE**

The charge of the incident photon is zero. After the interaction, electron-positrons have equal and opposite charges, therefore the sum is also zero. Hence charge is conserved.

2- CONSERVATION OF MOMENTUM

To conserve momentum, the presence of a heavy nucleus is necessary, which takes the recoil.

3- CONSERVATION OF ENERGY

The rest of mass of an electron is equal to the rest mass of the positron '$m_0\, c^2$'. Total rest mass energy of the pair is $2m_oc^2$. hence the minimum energy of the photon ($h\nu$) must be $2m_oc^2$ (1.02 MeV). The excess energy becomes the K.E of the pair.

$$h\nu = 2\, m_0\, c^2 + (K.E)_{e^-} + (K.E)_{e^+}$$

ANNIHILATION OF MATTER

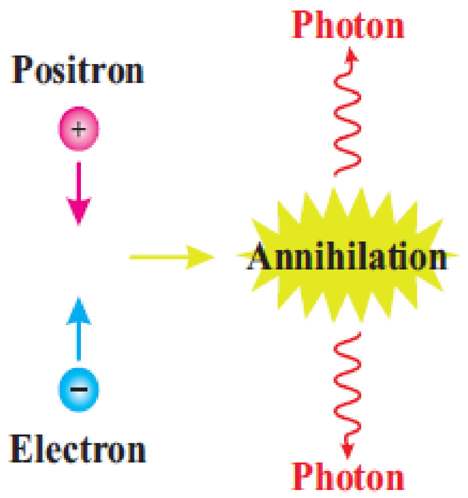
This is the reverse process of pair production in which energy is created from mass.

DEFINITION

The phenomenon in which a positron is in the vicinity of an electron, and two particles vanish, and their mass is converted into energy in the form of two photons is called annihilation.

INTERACTION DIAGRAM

In this process two photons are produced with the same energy. They move in opposite direction to conserve momentum. This phenomenon proves that matter and antimatter cannot co-exist in the same frame.



THEORY

Annihilation of matter obeys:
the law of conservation of charge
the law of conservation of momentum
the law of conservation of mass & energy.

$$(Rest\ mass\ energy\ of\ electron) + (rest\ mass\ energy\ of\ positron)$$
$$+(K.E)e^- + (K.E)e^+ = (energy\ of\ photons)$$
$$(m_0c^2)e^- + (m_0c^2)e^+ + (K.E)e^- + (K.E)e^+ = 2\,\gamma$$

WAVE NATURE OF PARTICLES

Classical physics traditionally treated particles and waves as separate and distinct entities.

However, the advent of quantum theory proposed a dual character for radiations, suggesting that they could exhibit characteristics of both waves and particles. The wave nature of particles implies that particles can behave like waves, displaying properties such as reflection, refraction, interference, diffraction, and other wave-like characteristics. In essence, this duality suggests that matter and radiation can co-exist in both particle and wave attributes. Examples of particles that exhibit this dual nature include:

(i) Matter particles, such as electrons, protons, and neutrons.

(ii) X-rays.
(iii) Photons.
(iv) Electromagnetic radiation.

THE DEBROLIE WAVE

In 1924 Louis de Broglie proposed that if electromagnetic radiation has a dual wave-particle aspect, material particles should also have a dual character.

De Broglie's idea suggested that both matter and energy could exhibit both particle and wave properties. This unified description was a departure from the classical distinction between particles and waves, providing a more comprehensive understanding of the behavior of particles at the quantum level.

DEBROLIE WAVELENGTH

The connection between a wavelike property 'λ' of radiation and particle-like property 'P' (momentum) is given by

$$\lambda = \frac{h}{P}$$

where *h* is Planck's constant. De Broglie suggested that this same relationship connects the particle-like and wavelike properties of matter. That is, with a moving particle of momentum P= mv, a wave is associated with having a wavelength λ given by

$$\lambda = \frac{h}{mv}$$

The wavelength of a particle given by this equation is called de Broglie wave or matter wave.

CONCLUSION

The wave and particle aspects of a moving body can never be observed at the same time. In certain situations, a moving body exhibits wave properties and in others, it exhibits particle properties.

THE DAVISSON AND GERMER EXPERIMENT

In 1927 Davisson and Germer performed an experiment to prove the de Broglie hypothesis.

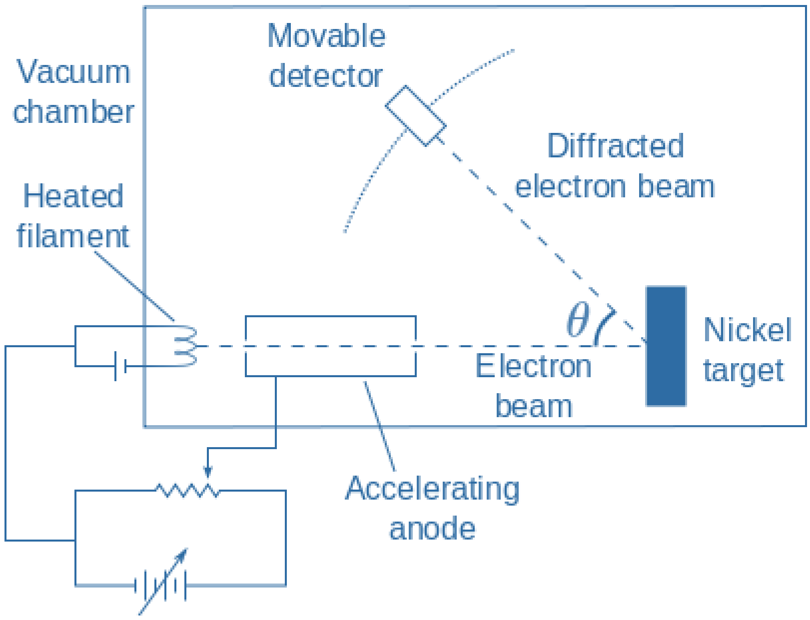
EXPERIMENT

They bombarded accelerated electrons on a Nickel crystal and measured the intensity of scattered electrons in a moveable detector.

It was observed that the electron scattered very strongly at certain angles only and not at other directions. The experimental parts are given as under:

1. An electron gun emits electrons via thermionic emission produced by the tungsten filament used in it, i.e., when heated to a specific temperature.
2 Two opposite-charged plates are known as the Electrostatic Particle Accelerator, which accelerates the electrons at a certain potential.
3 The accelerator is enclosed within a cylinder called a Collimator, which is a narrow passage for the electrons along its axis.
4. The target is a Nickel crystal on which the electron beam is fired normally.

5. When the electrons are scattered from Ni crystal, these are captured by the semicircular movable detector.



DAVISSSON GERMER EXPERIMENT AND DE GROGLIE RELATION

Let us consider an electron of mass (m_o), charge (e) accelerated from rest through a potential V. Then, the kinetic energy K. E of the electron equals to the work done (eV) on it by the electric field:

Then

$$K.E = eV$$

$$\frac{1}{2} m_0 v^2 = eV$$

$$m_0 v^2 = 2\, eV$$

$$m_0^2 v^2 = 2m_0\, eV$$

$$(m_0\, v)^2 = 2m_0\, eV$$

$$\sqrt{(m_0\, v)^2} = \sqrt{2m_0\, eV}$$

$$m_0\, v = \sqrt{2m_0\, eV}$$

$$P = \sqrt{2m_0\, eV} \quad \dots\dots\dots\dots\dots (i)$$

Using de Broglie equations,

$$\lambda = \frac{h}{P}$$

Substituting the value of momentum from equation (i) in the above equation, we get

$$\lambda = \frac{h}{\sqrt{2m_0\, eV}}$$

The wavelength calculated from this formula agreed with the one that was calculated by using Bragg's equation for diffraction. Thus Davison-Germer experiment provides a direct verification of de Broglie's hypothesis.

CALCULATION FOR ELECTRON AT VOLTAGE V

We know that

$$\lambda = \frac{h}{\sqrt{2m_0\, eV}}$$

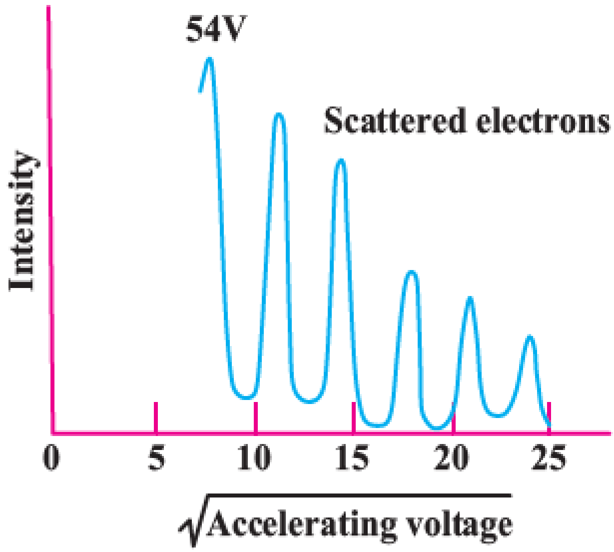
$$\lambda = \frac{6.626 \times 10^{-34}}{\sqrt{2(9.1 \times 10^{-31})(1.6 \times 10^{-19})V}}$$

$$\lambda = \frac{1.22}{\sqrt{V}}\ nm$$

Where V is the magnitude of accelerating potential in volts.
The de Broglie wavelength is associated with electrons for V = 54 V from the graph, then we have

$$\lambda = \frac{1.22}{\sqrt{54}}\ nm$$

$$\lambda = 0.167\ nm$$



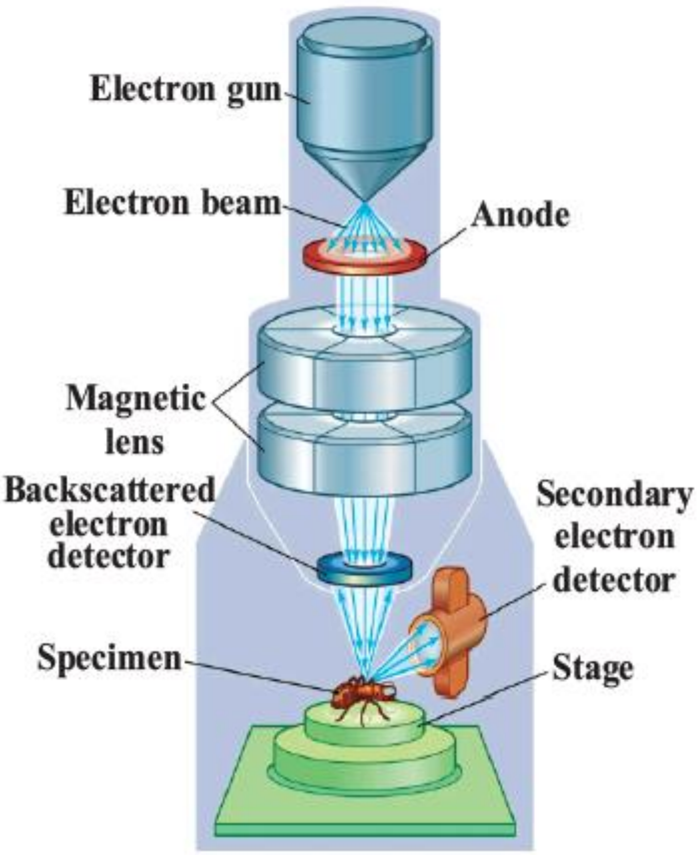
We conclude that this experiment confirms the wave nature of electrons and the de Broglie relation.

ELECTRON MICROSCOPE

De Broglie's hypothesis are used in the field of electron optics. In the electron microscope
design, the wave properties of electrons have been utilized with higher resolution, which is giving a great improvement in visualization.

An electron microscope is a microscope that uses a beam of accelerated electrons as a source of illumination. It is a special type of microscope having a high resolution of images, able to magnify objects in nano meters, which are formed by controlled use of electrons in a vacuum captured on a phosphorescent screen.

Ernst Ruska (1906-1988), a German engineer and academic professor, built the first Electron Microscope (EM) in 1931, and the same principles behind his prototype still govern modern EMs. De Broglie's hypothesis of electron wave paved the way for the development of the electron microscope (EM), which can produce images of much greater magnification than an optical microscope. There are two types of electron microscopes which are transmission electron microscope (TEM), which produces a two-dimensional image, and scanning electron microscope (SEM), which produces images with a three-dimensional.



WORKING PRINCIPLES

Electron microscopes use signals arising from the interaction of an electron beam with the sample to obtain information about structure, morphology, and composition.

1. The electron gun generates electrons.
2. Two sets of condenser lenses focus the electron beam on the specimen and then into a thin tight beam.
3. To move electrons down the column, an accelerating voltage (mostly between 100 kV-1000 kV) is applied between the tungsten filament and anode.
4. The specimen to be examined is made extremely thin, at least 200 times thinner than those used in the optical microscope. Ultra-thin sections of 20-100 nm are cut which is already placed on the specimen holder.
5. The electronic beam passes through the specimen and electrons are scattered depending upon the thickness or refractive index of different parts of the specimen.
6. The denser regions in the specimen scatter more electrons and therefore appear darker in the image since fewer electrons strike that area of the screen. In contrast, transparent regions are brighter.
7. The electron beam coming out of the specimen passes to the objective lens, which has high power and forms the intermediate magnified image.
8. The ocular lenses then produce the final further magnified image.

APPLICATIONS OF ELECTRON MICROSCOPY

Electron microscopes are widely used to investigate the structure of an extensive range of biological samples and inorganic materials including micro-organisms, cells, large molecules, metals, and crystals.

In life sciences, electron microscopy is utilized to investigate the molecular nature and mechanisms of disease. Also, it enables scientists to view the 3D structure of biological tissues or cells, verify the structure of proteins, and study viruses in a biological context.

In industry it is mainly used for quality control and failure analysis, also it is widely used whenever the characterization of materials is needed in forensic science, mining, petrochemical, food science, etc.

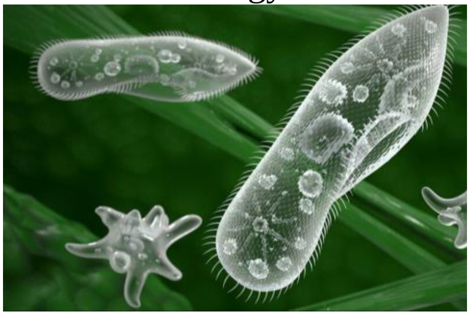
The advancement of microbiology is significantly indebted to the electron microscope, which has revolutionized our understanding of microorganisms such as bacteria, viruses, and other pathogens, thereby greatly enhancing the effectiveness of disease treatments.

ROLE OF ELECTRON MICROSCOPE

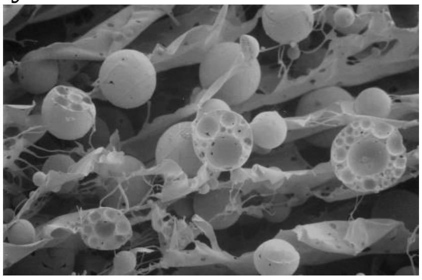
1. **Higher Resolution**:

Electron microscope offers significantly higher resolution compared to optical microscopes, allowing observation at the nanometer scale due to the shorter wavelength of electrons.

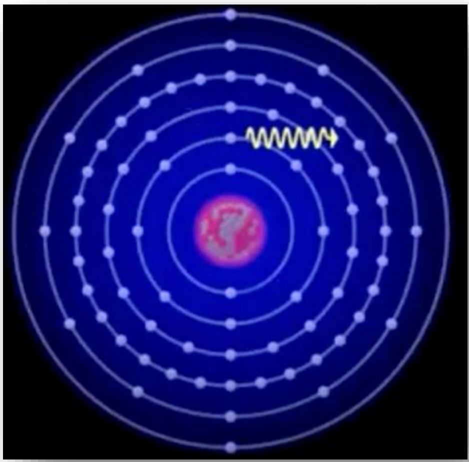
2. **Transmission Electron Microscope (TEM)**: TEMs study the internal structures of thin specimens, producing detailed images of cells, organelles, and crystalline structures. Valuable in biology, materials science, and nanotechnology.



3. **Scanning Electron Microscope (SEM):** SEMs provide 3D surface images by scanning specimens and detecting emitted secondary electrons. Widely used in biology, geology, and materials science for surface analysis.

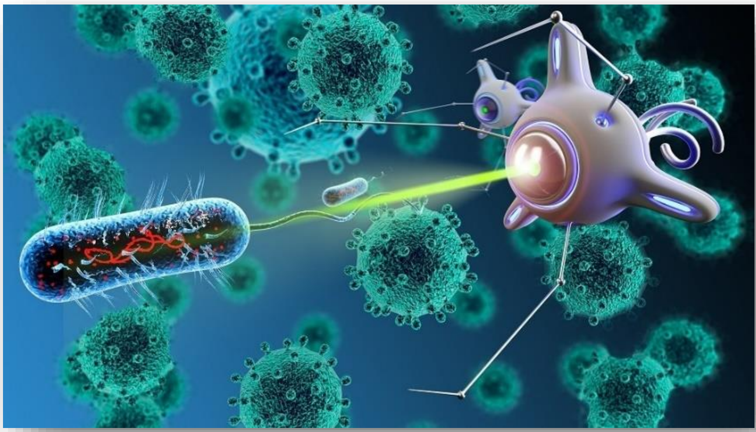


4. **Energy-Dispersive X-ray Spectroscopy (EDS):** With EDS detectors, electron microscopes analyze elemental composition by detecting X-rays emitted when high- energy electrons interact with the sample.

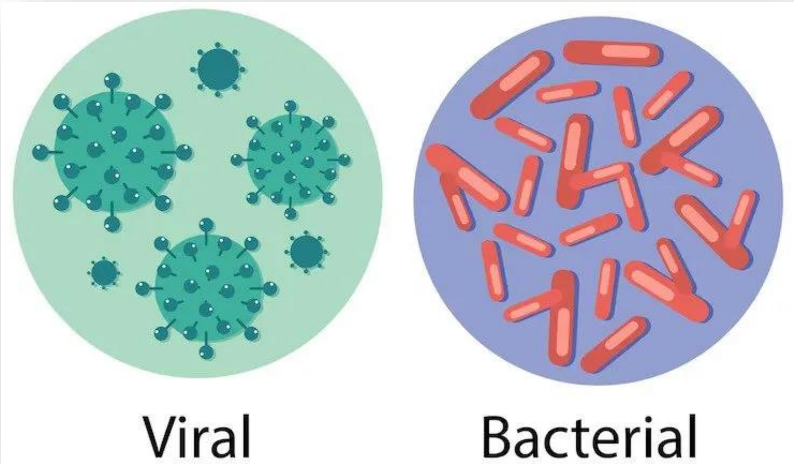


5. Materials Science: Crucial for studying the microstructure of materials, aiding understanding of relationships between microstructure and properties in metals, ceramics, and polymers.

6. Nanotechnology: Essential for imaging and characterizing nano-materials, contributing to the development of new materials and devices through observation and manipulation of nano-particles and nanostructures.



7. Advancements in Medicine: Contributes to medical research by providing insights into the structure of viruses, bacteria, and cellular organelles, aiding understanding of diseases and therapeutic development.



8. Quality Control in Industry: Used across industries for quality control and failure analysis, helping identify defects, analyze material composition, and ensure product integrity at the microscopic level.

HEISENBERG UNCERTAINTY PRINCIPLE

INTRODUCTION

The coordinates and velocity of a particle could be specified with absolute precision in classical physics. However, there is a fundamental limitation to the accuracy with which the position and velocity of microscopic particles can be determined – no matter how refined we make our instruments. This limitation is because microscopic particles exhibit wave properties.

STATEMENT

It states that it is impossible to measure simultaneously, certain pairs of properties of a subatomic particle, such as its position and momentum, with absolute certainty.

The formal inequality relating to the standard deviation of position x and the standard deviation of momentum p is given here:

$$\Delta x \Delta P \geq \frac{h}{4\pi}$$

where ΔP refers to uncertainty in the momentum of a particle, Δx refers to uncertainty in the position of a particle and h is Planck's universal constant (6.625×10^{-34} J.s).

$$\Delta x \Delta P \geq \frac{h}{2\pi} \times \frac{1}{2}$$

$$\Delta x \Delta P \geq \hbar \times \frac{1}{2}$$

$$\Delta x \Delta P \geq \frac{\hbar}{2}$$

ħ (pronounced "h-bar") is the reduced Planck constant.

Heisenberg uncertainty principle can also be applied to other pairs of complementary quantum properties, such as energy and time

$$\Delta E \, \Delta t \geq \frac{h}{2}$$

Here, ΔE and Δt represents the uncertainties in the energy and time respectively.

As an example, the period that elapses between the excitation of an atom and the time it radiates is 10^{-8} seconds. The photon energy is uncertain by an amount of 10^{-26} J. The frequency of the radiation emitted by the atom is uncertain by 10^{7} H_z.

APPLICATION

The principle introduces the concept of determinism in physics.

It reveals wave-particle duality. It indicates that it is impossible to design an experiment that shows the wave and particle aspects of matter (or radiation) at the same time.

It gives the probability of finding a particle in a given space in place of certainty.

The limitation imposed by the uncertainty principle in the realm of atoms suggests that Bohr's orbits are not well-defined. We can only talk about the probability of finding an electron in a certain region around a nucleus.

The principle helps to prove that electrons are not present inside atomic nuclei.

SHORT REASONING QUESTIONS

1 difference between wave and particle.

	PARTICLE.	WAVE
1	A particle occupies a well-defined position in space i.e. a particle is localized in space e.g. a toy, sand, a cricket ball, etc	A wave is spread out in space e.g. by throwing a stone in a pond of water, the waves start moving out in the form of concentric circles. Similarly, the sound of the speaker reaches everybody in the audience. Thus a wave is delocalized in space
2	When a particular space is occupied by one particle, the same space cannot be occupied simultaneously by any other particle. In other words, particles do not interfere.	Two or more waves can coexist in the same region of space and hence interfere.
3	Particles follow classical mechanics principles, such as Newton's laws. They can collide and interact but do not exhibit wave-like behavior such as interference.	Waves exhibit properties such as interference and diffraction. They can overlap and combine, leading to phenomena like constructive and destructive interference.

2 Is it possible for the de Broglie wavelength of a particle?

Ans **PARTICLE AT REST**

The De Broglie wavelength (λ) of a particle is given by the formula:

$$\lambda = \frac{h}{P}$$

For a particle at rest, its momentum p is zero(P = 0)

$$\lambda = \frac{h}{0}$$

Since division by zero is undefined, the De Broglie wavelength of a particle at rest is technically undefined.

MOVING PARTICLE

Yes, that is possible. The momentum of the particle dictates its de-Broglie wavelength,

$$\lambda = \frac{h}{P}$$

De-Broglie wavelength for any moving object such as a tennis ball or football or smaller like the smallest particles in nature such as nuclear particles, but for the macroscopic object such as the ball has a smaller de-Broglie wavelength than their dimension.

3. Estimated Broglie wavelength of a cricket ball on the pitch?

Ans consider a cricket ball of 200g on the pitch moving with a velocity of 20 m/s. The de Broglie wavelength associated with a ball is given by

$$\lambda = \frac{h}{mv}$$

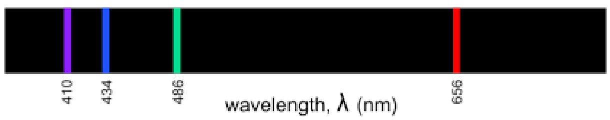
$$\lambda = \frac{6.626 \times 10^{-34}}{(0.2)(20)}$$

$$\lambda = 1.657 \times 10^{-34}\, m$$

The de Broglie wavelength of a cricket ball is very small and unobservable.

4 Differentiate between the continuous and discrete emission of radiation?

Ans

	CONTINUOUS SPECTRUM	DISCRETE SPECTRUM
1	A continuous spectrum contains all wavelengths or frequencies within a given range without any gaps.	A discrete spectrum consists of distinct lines or bands at specific wavelengths or frequencies, with gaps between them.
2	The light from a prism that splits white light into a rainbow shows a continuous spectrum, where all colors blend smoothly into one another 	The emission spectrum of a gas like hydrogen shows discrete lines at specific wavelengths, corresponding to the energy levels of electrons in the atom 
3	Incandescent, high temperature, solids emit continuous spectra	electrons can fall into neighboring atoms during de-excitation and emit all possible frequencies. Excited gases emit discrete spectra

5 What is threshold frequency?

Ans The minimum frequency of incident electromagnetic radiation (photon) required to remove a photoelectron from the surface of a metal is called **threshold frequency.**

If the incident photons do not have a high enough frequency (f) and energy to overcome the work function (Φ)of the plate, then no electrons will be emitted.

6. How has the photoelectric effect been applied in real-world technologies or devices, and what are its practical implications?

Ans Technological innovations continue to expand the applications of the photoelectric effect, driving advancements across various fields.

SOLAR PANEL

Solar panel convert light energy into electricity with the help of Photoelectric effect. When the photons of sunlight fall on the semiconductor installed on the solar panel, they displace the electrons from their atoms, and the movement of electrons causes generate electricity.

LIGHT SENSORS

Photocells are used in light sensors, when light falls on the photocells it creates electric energy which can be used to trigger various switches like automatic light on-off systems.

DIGITAL CAMERAS

CMOS (Complementary Metal-Oxide-Semiconductor) or CCD (Charge-Coupled Device) sensor is used in digital cameras which uses the principles of photoelectric effect which converts light energy into electrical signals. These electrical signals are used to create digital images.

BARCODE SCANNERS

Photodiodes are used in the scanner when it placed on the barcode intensity of the light changes. Photoelectric effect is used to convert these lights into digital which can be used to identify the product.

ELECTRON MICROSCOPES:

Electron microscopes utilize the emission of electrons for imaging at micro and nano scales

7 What are the advantages of an electron microscope over an optical microscope?

Ans The advantages of an electron microscope over an optical microscope include:

High-Resolution Imaging: Electron microscopes provide extremely high-resolution images that can reveal fine details of samples, far surpassing the capabilities of optical microscopes.

Depth of Field: They offer a much greater depth of field, enabling better viewing of three-dimensional structures.

Magnification: Electron microscopes can achieve much higher magnifications, allowing for the analysis of extremely small structures at the nanoscale.

8. Is it possible to create only an electron through matter and photon interaction?

Ans No, it is not possible to create only an electron through the interaction of a photon with matter. According to the principles of quantum electrodynamics (QED), any photon that has enough energy to create an electron must also create its antiparticle, which is a positron. This process is known as pair production.

In summary, the creation of just an electron from photon-matter interaction, without the accompanying positron, is not allowed by the conservation laws of physics.

9 Give construction of electron microscope?

Ans (see notes)

10. Elaborate the particle nature of electromagnetic radiation.

Ans Albert Einstein took help from Max Planck's black body radiation and expanded his experiments further to prove the particle nature of light. He conducted the photoelectric effect which showed that electrons are emitted from atoms when they absorb energy from radiation and light. Thus, the photoelectric effect proved the existence of the particle nature of light.

The energy of Photon: $E = h\upsilon$

$$E = \frac{hC}{\lambda}$$

Here

E = energy of the photon,

h = Planck's constant ($h = 6.62\times10^{-34}$ J-s)

υ = frequency of the photon,

c = speed of light

λ = wavelength of photon.

The intensity of a light is directly proportional to the photons present in it.