DAWN OF MODERN PHYSICS

INTRODUCTION

In the begining of 20TH century, many experimental and theoratical problems remained unresolved. The laws of classical physics are valid in ordinary processes of everyday life but these laws were not successful to explain the behaviour of matter on the atomic level and phenomena like black body radiation, the photoelectric effect, Compton effect, the emission of sharp spectral lines by atoms in a gas discharge tube and the invariance of the speed of light.

In order to explain the behaviour of tiny or very fast moving particles and phenomena like black body radiation, the photoelectric effect etc, a new physics was developed at the end of 19TH century known as modern physics.

The main branches of modern physics are

(i) Relativity.

(ii) Quantum Theory.

RELATIVITY

That branch of modern physics which deals with the study of those objects moving with relativistic speeds, called relativity or relativistic mechanics.

Those speeds of objects which are approaching the speed of light, called relativistic speeds

$$\text{Relativistic Speed} \cong \frac{1}{10} \times (\text{Speed of Light})$$

QUANTUM THEORY

That theory which explains the behaviour of electromagnetic radiations as discrete packets of energy and those particles in which the wave properties are dominated, called quantum theory.

That branch of modern physics which deals with those particles behave as waves is called quantum mechanics.

NEW CONCEPTS OF MODERN PHYSICS

(i) There is no such thing as ether.

(ii) All the laws of physics are hold good in inertial frames of refrence.

(iii) The speed of light in free space has the same value for all observers, regardless of their state of motion.

(iv) Mass and energy are interconvertible. Mass can be converted into energy and energy can be converted into mass under certain circumstances.

(v) Waves and particles are not two different entities. Waves can behave as particles and particles can behave as waves under certain circumstances.

(vi) Light consists on small energy packets or bundles, known as quantas each having frequency "f" and energy "hf".

(vii) All the motions are relative. There is no such thing as absolute rest or absolute motion.

(viii) Accuracy can not be measured better than $\hbar = h/2\pi$. Where

h = Plank's constant

$= 6.63 \times 10^{-34}$ J.s

REST

A body is said to be at rest if it does not change its position with respect to its surroundings.

MOTION

A body is said to be in motion if it changes its position with respect to its surroundings.

RELATIVE MOTION

The change of position of a body with respect to another body is called relative motion.

EXPLANATION

Consider that a ball is thrown up. The 'up' direction is only for that particular place. Its position will be 'down' for a person on the opposite side of the globe. The concept of direction is purely relative. Similarly, the rest and motion of an object is not same for different observers. So, all the motions are relative to a person or instrument observing it.

EXAMPLE

The walls of the cabin of a moving train are stationary with respect to the passengers sitting inside it but are in motion to a person stationary on the ground. So we cannot say whether an object is absolutely at rest or absolutely in motion.

Hence, all motions are relative.

EXPERIMENT

Consider two cars are moving with constant velocities in any direction. Let a ball is thrown straight up. It will come back straight down. This will happen in both the cars.

Now consider that one car is stationary and other is moving with constant velocity. The person in the moving car throws a ball straight up. He will receive the ball straight down. But the person sitting in the stationary car observes that the path of the ball is parabola. So, the observations in some frame of refrence are identical with the experiment but different for other frame of refrence.

Hence, we conclude that all the motions are relative and there is no absolute motion or absolute rest.

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FRAME OF REFRENCE

A coordinate system with respect to which measurements are made is called frame of refrence.

Cartesian or rectangular coordinate system is the simplest frame of refrence. Cartesian coordinate system consists of three mutually perpendicular lines represented as X-axis, Y-axis and Z-axis.

EXAMPLES

⇒ The position of a table in a room can be located relative to the walls of the room. So the room is the frame of refrence.

⇒ For measurements taken in the laboratory, the laboratory is the frame of refrence.

⇒ If the experiment performed in a moving train, then train is the frame of refrence.

⇒ The position of a spaceship can be located relative to the position of stars. So a coordinate system based on these stars is the frame of refrence.

TYPES OF FRAME OF REFRENCE

There are two types of frame of refrence

(i) Inertial frame of refrence

(ii) Non-inertial frame of refrence

INERTIAL FRAME OF REFRENCE

A coordinate system in which the law of inertia is valid, is called frame of refrence.

OR

A coordinate system which is at rest or moving with uniform velocity, is called inertial frame of refrence.

So, inertial frame of refrence is a non-accelerated frame of refrence i-e; $a = 0$.

EXPLANATION

In an inertial frame of refrence, a body at rest will remain at rest unless acted upon an unbalanced force. For example, a book lying on a table will remain at rest untill it is lifted. Other laws of nature also apply in such a frame of refrence.

Similarly, if we place a body upon Earth, it remains at rest unless an unbalanced force is applied on it. So, in this case, Earth may be considered as an inertial frame of refrence.

A body placed in a car moving with uniform velocity with respect to Earth also remains at rest, so a moving car is also an inertial frame of refrence. Hence, any frame of refrence which is moving with uniform velocity with respect to an inertial frame is also an inertial frame.

NON-INERTIAL FRAME OF REFRENCE

A coordinate system in which the law of inertia is not valid, called an non-inertial frame of refrence.

OR

A coordinate system which is moving with non-uniform velocity, called a non-inertial frame of refrence.

So, non-inertial frame of refrence is an accelerated frame of refrence i-e; $a \neq 0$.

EXPLANATION

When a car is suddenly stopped or accelerated, then the body placed in it, no longer remains at rest. In this case, the car is not an inertial frame of refrence. Hence, an accelerated frame is a non-inertial frame of refrence.

NOTE

Earth is a non-inertial frame of refrence. Earth can often be treated as an inertial frame of refrence because of very small acceleration.

SPECIAL THEORY OF RELATIVITY

The branch of relativity which deals with the problems involving inertial or non-accelerating frames of refrence is called special theory of relativity.

GENERAL THEORY OF RELATIVITY

The branch of relativity which deals with the problems involving non-inertial or accelerating frames of refrence is called general theory of relativity.

POSTULATES OF SPECIAL THEORY OF RELATIVITY

The special theory of relativity is based upon two postulates which can be stated as

POSTULATE I

The laws of physics are the same in all inertial frames.

POSTULATE II

The speed of light in free space has the same value for all the observers, regardless of their state of motion.

EXPLANATION OF POSTULATE I

The first postulate tells us about the fact that all physical laws are the same in frames of refrence moving with uniform velocity with respect to one another. If the laws of physics were different for different observers in relative motion, then the observer could decide the difference that which of them were stationary in free space and which were moving. But such a distinction does not exist. So first postulate implies that there is no way to detect absolute uniform motion.

Hence, all the motions are relative, there is no absolute motion or rest.

Explanation Of Postulate II

The second postulate states an experimental fact that the speed of light in free space is the universal constant 'C'.

The speed of light 'C' is given as

$$\boxed{C = 3 \times 10^{8}\, m.s^{-1}}$$

Results Of Special Theory Of Relativity

Some interesting results of special theory of relativity are discussed below:

Time Dilation

According to special theory of relativity, time is not an absolute quantity. It depends upon the motion of the frame of reference.

Consider an observer is stationary in an inertial frame of reference. He measures the time interval between two events in this frame. Let this time be 't_0'. This time is known as proper time.

If the observer is moving with respect to the frame of refrence of events with velocity 'v' or if the frame of events is moving with respect to the observer with velocity 'v', then the time measured by the observer would not be 't_0' but it would be 't' given as

$$\boxed{t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}} \longrightarrow (1)$$

Where 'C' is the speed of light ($3\times10^{8}\ m.s^{-1}$).
As the quantity $\sqrt{1-v^2/c^2}$ is always less than one (1) because 'v' is always less than 'c', so 't' is greater than 't_o' i-e; time has dilated or stretched due to relative motion of the observer and the frame of refrence of events.

This interesting result applies to all the timing processes such as physical, chemical and biological processes. Even aging process of the human body is slowed down by motion at very high speeds approaching speed of light.

LENGTH CONTRACTION

The distance from Earth to a star measured by an observer in a moving spaceship seems to be smaller than the distance measured by an observer on Earth. Similarly, the distance between two points appears shorter for an observer which is in motion relative to the two points than if observer at rest relative to the two points. This effect is known as length contraction.

Let

l_o = Length of an object or distance between two points measured by an observer who is relatively at rest, called proper length.

And if

l = Length of the same object or distance between same two points measured by an observer who is in relative motion with respect to the object with velocity 'v'.

Now according to special theory of relativity the contracted length 'l' is given as

$$\boxed{l = l_o\sqrt{1-\frac{v^2}{c^2}}} \longrightarrow (2)$$

Because 'v' is less than 'c', so the quantity $\sqrt{1-v^2/c^2}$ is also less than one (1) i-e;

$$\sqrt{1-\frac{v^2}{c^2}} < 1$$

Hence $$l < l_o$$

So, the length measured in the moving spaceship would be smaller than it is measured at rest on the earth.

Condition For Length Contraction

The length contraction happens only along the direction of motion. No length contraction observed perpendicular to the direction of motion.

Mass Variation or Increase In Mass

According to special theory of relativity mass of an object increases with its speed. Let

m_o = Mass of the object at rest, and

m = Mass of the object when it is moving with certain speed 'v'.

Then according to special theory of relativity, the masses m and m_o are related as

$$\boxed{m = \frac{m_o}{\sqrt{1-\frac{v^2}{c^2}}}} \longrightarrow (3)$$

As $v < c$, so $\sqrt{1-\frac{v^2}{c^2}} < 1$ and $m > m_o$. i-e; mass of object increases with increasing speed.

Question: Why ordinary objects are not moving with the speed of light? i-e; $v \neq c$.

According to special theory of relativity, the mass of an object moving with speed 'v' is

$$m = \frac{m_o}{\sqrt{1-v^2/c^2}}$$

As the speed of the object approaches to speed of light 'c', its mass increases and it requires a greater force to change the speed of the object. Hence

$$v \longrightarrow c \quad \text{then} \quad \frac{v}{c} \longrightarrow 1$$

and

$$\sqrt{1-\frac{v^2}{c^2}} \longrightarrow 0$$

So above equation becomes as

$$m \longrightarrow \frac{m_0}{0}$$

or

$$\boxed{m \longrightarrow \infty}$$

So mass of body moving with speed of light becomes infinite and according to Newton's seconds law of motion

$$F = ma$$

or

$$F = (\infty)\, a$$

or

$$F = \infty$$

Hence infinite mass requires an infinite force to accelerate it. As infinite forces are not available, so, an object cannot be accelerated to the speed of light 'c' in free space.

QUESTION: <u>Why we cannot observe relativistic effects in everyday life?</u>

In our everyday life, the objects move with extremely small speeds as compared to the speed of light i-e; $v <<< c$.

As Earth's orbital speed is only $30\ Km.s^{-1}$! On the other hand, the speed of light in free space is $300,000\ Km.s^{-1}$ which is very large as compared to the Earth's orbital speed. This is the reason why Newton's laws are valid in everyday life. On the other hand, for atomic and sub-atomic particles moving with velocities approaching speed of light, the relativistic effects are observed.

Mass – Energy Relation

According to special theory of relativity, mass and energy are different quantities but are interconvertible. The total energy 'E' and mass 'm' of an object moving with velocity 'v' approaching speed of light are related by the expression

$$\boxed{\text{Total Energy} = E = mc^2} \longrightarrow (1)$$

Where 'c' is the speed of light ($3\times10^8\,m.s^{-1}$) and 'm' is the mass of the object depends upon the speed of the object.

Similarly, the energy equivalent of an object's rest mass 'm_o' is called rest mass energy 'E_o' given by the relation as

$$\boxed{\text{Rest Mass Energy} = E_o = m_oc^2} \longrightarrow (2)$$

As $m > m_o$, so total energy 'mc^2' is greater than rest mass energy 'm_oc^2'. The difference in energy represents the K.E. of the mass. So, we can write

Total Energy = Rest Mass Energy + K.E.

$\Rightarrow$ $E = E_o + K.E.$

$\Rightarrow$ $mc^2 = m_oc^2 + K.E.$

$\Rightarrow$ $K.E. = mc^2 - m_oc^2$

$\Rightarrow$ $\boxed{K.E. = (m - m_o)c^2} \longrightarrow (3)$

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Here K.E. represents the change or increase in energy 'ΔE' of the object and $(m - m_o)$ represents the change or increase in mass 'Δm'.

So, equation (3) becomes as

$$\Delta E = \Delta m . c^2$$

$\Rightarrow$ $\boxed{\Delta m = \dfrac{\Delta E}{c^2}} \longrightarrow (4)$

As 'c^2' is very large quantity, so significant changes in mass require very large changes in energy according to equation (4). In our everyday life, energy changes are too small to provide measureable mass changes. However, in nuclear reactions, energy and mass changes are found to be exactly in accordance with equation ④.

NAVSTAR Navigation System

The results of special theory of relativity are used practically even in everyday life by a modern system of navigation satellites, called **NAVSTAR.**

This system can be used to determine the location and speed anywhere on Earth to an accuracy of about $2.0\ cm.s^{-1}$. However, if relativity results are not used, then speed can not be determined any closer than about $20\ cm.s^{-1}$.

Using these results, the location of an aircraft after an hour's flight can be predicted to about 50m as compared to about 760m without using relativistic effects.

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Black Body Radiation

Black Body

A body which absorb all the radiations incident on it, called a black body.

Radiation

It is the continuous emission of energy from the surface of all the bodies in the form of electromagnetic waves which travel with the speed of light, called radiation.

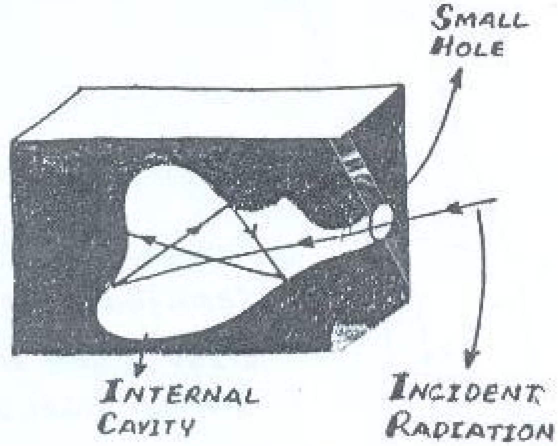
Dependance Of Radiation Upon Temperature And Their Wavelength

When a body is heated, it emits radiation. The nature of radiation depends upon the temperature. At low temperature, a body emits radiation of long wavelengths in the invisible infrared region. At high temperature, a body emits radiation of shorter wavelength. So, the amount of emitted radiation is different for different wavelengths.

For Example, when platinum wire is heated, it appears dull red at about 500°C, it changes to cherry red at 900°C, becomes orange red at 1100°C, yellow at 1300°C and finally white at about 1600°C. This shows that as the temperature rises, the wavelength of the radiation decreases and hence energy of radiation increases.

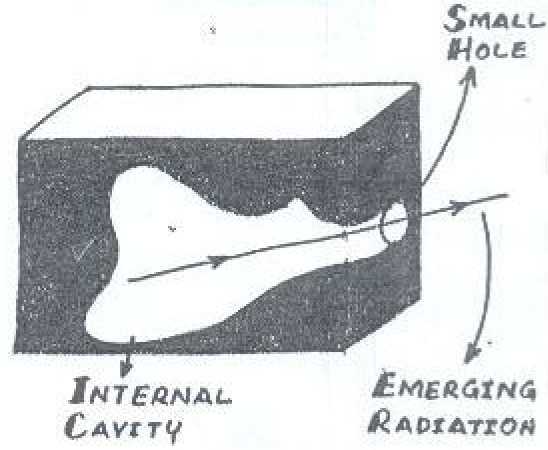
Construction Of Black Body

In order to understand the distribution of radiation emitted from a hot body, we consider a non-reflecting object such as a solid block which has a hollow cavity within it. It has a small hole and the radiation can enter or escape only through this hole. The inside surface of the cavity is blackened with lamp black so that it becomes as good an absorber and as bad a reflector as possible. The small hole appears black because the



(Absorption Of Radiation)

Figure (a)



(Emission Of Radiation)

Figure (b)

radiation that enters is reflected from the inside walls many times and a part of this radiation is absorbed at each reflection until none remains. Such a body is called black body and has the property to absorb all the radiation entering it. A black body is both an ideal absorber and an ideal radiator as shown in figure (a) and (b).

Black Body Radiation

When a black body is heated at certain uniform temperature, then the radiation emitted from the black body are called black body radiation or temperature radiation or cavity radiation or full radiation or perfect radiation.

Intensity Distribution Diagram

Lummer and Pringsheim measured the intensity of emitted energy of different wavelengths radiated from a black body at different temperatures by the apparatus as shown in figure (c).

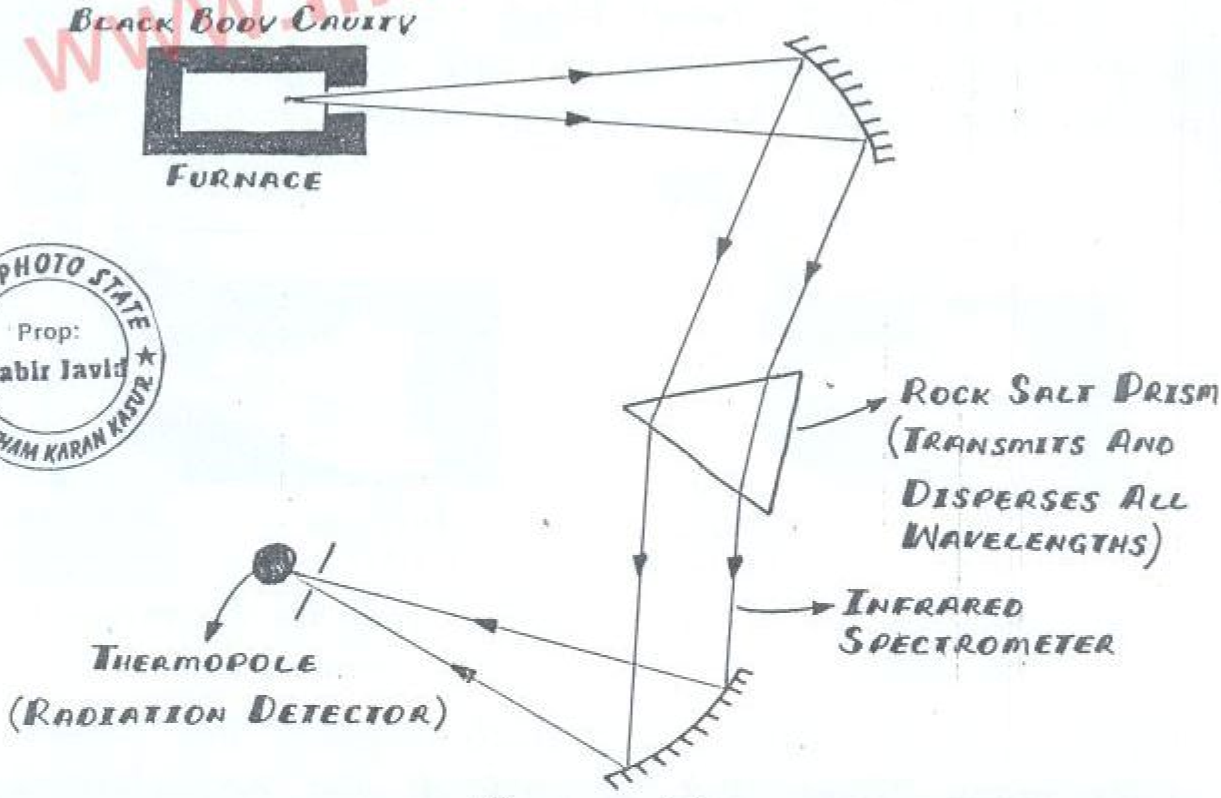
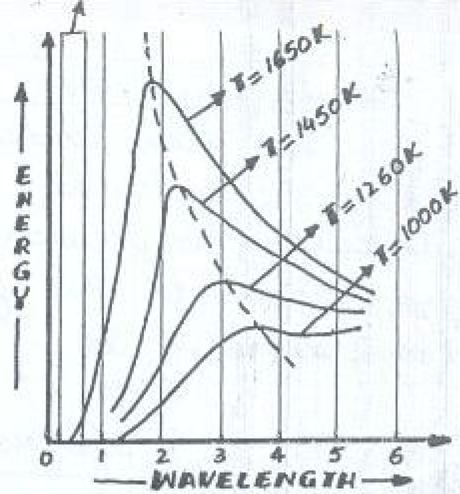


Figure (C)

The amount of radiation emitted with different wavelengths is shown in the form of energy distribution curves for each temperature as shown in the figure (d).



The curves reveal the following interesting results.

1. NON-UNIFORM ENERGY DISTRIBUTION

At a given temperature, the energy is not uniformly distributed in the radiation spectrum of the body.

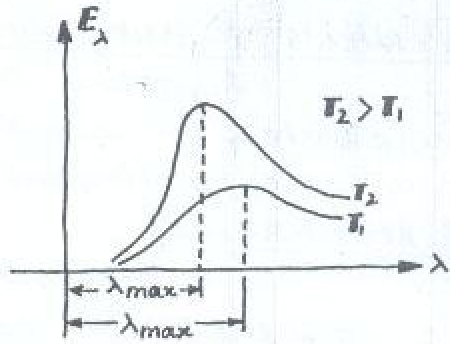
2. RELATION BETWEEN λ_{max} AND T

At a given temperature T, the emitted energy has maximum value for a certain wavelength λ_{max} and the product $\lambda_{max} \times T$ remains constant. i-e;

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

or $$\lambda_{max} = \frac{\text{CONSTANT}}{T}$$

or $$\boxed{\lambda_{max} \times T = \text{CONSTANT}}$$



The value of the constant is about 2.9×10^{-3} m.K. The above equation shows that as T increases, λ shifts to shorter wavelength.

3. SHAPE OF INTENSITY DISTRIBUTION DIAGRAM

For all wavelengths, an increase in temperature causes an increase in energy emission. The radiation intensity increases with increase in wavelengths and at a particular wavelength λ_{max}, it has a maximum value. With further increase in wavelength, the intensity of radiation decreases.

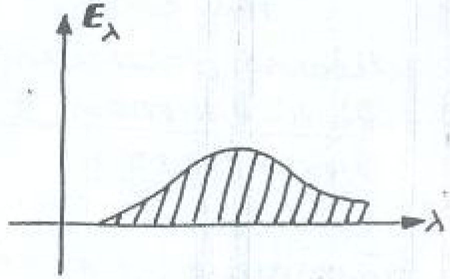
4. Stephen-Boltzmann Law or Area Under Intensity Distribution Curve

The area under each curve represents the total energy (E) radiated over all wavelengths at a particular temperature. It is found that is directly proportional to the fourth power of the Kelvin temperature T. So

$$E \propto T^4$$

or $$E = (\text{Constant})\, T^4$$

or $$\boxed{E = \sigma T^4}$$



Where 'σ' is called Stephen's constant and its value is

$$\sigma = 5.67 \times 10^{-8}\ W \cdot m^2 \cdot K^{-4}$$

The above relation is known as Stephen-Boltzmann law.

Planck's Assumption

According to Max Planck, energy is radiated or absorbed in discrete packets, called quanta rather than as a continuous wave.

Explanation

Maxwell's electromagnetic wave theory of radiation can not explain the energy distribution along intensity - wavelengths curves. According to this theory, energy is radiated or absorbed in the form of continuous waves.

In 1900, Max Planck successfully explains the shape of energy distribution curves. He introduced a mathematical model resulting in an equation that describes the energy radiated or absorbed in the form of discrete packets, called quanta. According to Planck, energy 'E' of each quanta is directly proportional to its frequency 'f'. i-e;

$$E \propto f$$

or $$E = (\text{CONSTANT}) f$$

or $$\boxed{E = hf}$$

Where 'h' is Planck's constant and its value is

$$h = 6.63 \times 10^{-34}\ J.s$$

This fundamental constant 'h' is as important as the constant c, the speed of light in vacuum.

Max Planck received the Nobel prize in physics in 1918 for his discovery of energy quanta.

THE PHOTON

Light consists of indivisible tiny bundles of energy, called photons.

EXPLANATION

According to Max. Planck, matter is not continuous but consists of a large number of tiny or small particles. Similarly, the radiation energy emitted from a source is not continuous but consists of small energy packets or bundles of energy, known as quantas.

Einstein extended Plancks idea and postulated that packet or tiny bundles of energy are integral parts of all electromagnetic radiation and are not subdivided. These indivisible tiny bundles of energy, he called photons. A beam of light with wavelength 'λ' consists of stream of photons moving with speed of light 'c' and each photon has energy directly proportional to the frequency 'f' as

$$E \propto f$$

or $$E = (\text{CONSTANT}) f$$

or $$\boxed{E = hf}$$

Where 'h' is Planck's constant and its value is $6.63 \times 10^{-34}\ J.s$.

Momentum Of Photon

According to theory of relativity, the energy of photon is related momentum of photon 'p' as

$$E = mc^2$$

or $$E = mc \cdot c \qquad (\because p = mc)$$

or $$E = pc \longrightarrow (1)$$

As energy of photon is

$$E = hf \longrightarrow (2)$$

Comparing equation (1) and (2)

$$pc = hf$$

or $$\boxed{p = \frac{hf}{c}} \longrightarrow (3)$$

For photon, $c = f\lambda$

$$\therefore \quad p = \frac{hf}{f\lambda}$$

or $$\boxed{p = \frac{h}{\lambda}} \longrightarrow (4)$$

Equation (3) and (4) gives the momentum of photon.

Energy Of Detectable Photons

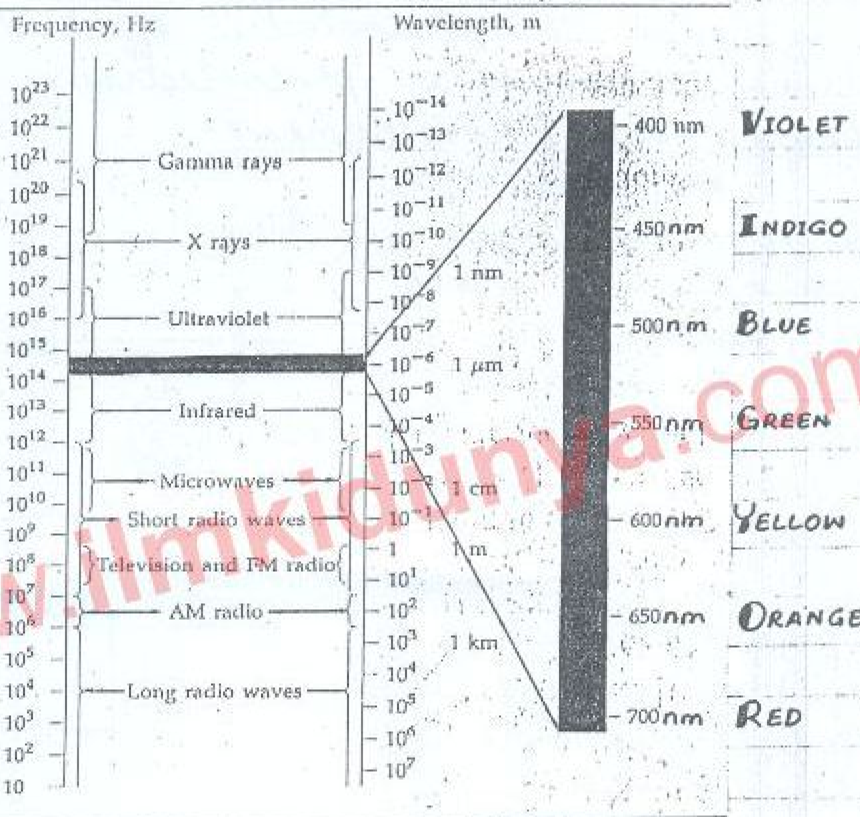
Q. How Photons are detected?

The high energy photons are easily detected. For example, γ-radiation with energy nearly equal to 1 MeV is easily detected as quanta by a radiation detector and counter. The radio waves photons with energy about 10^{-10} eV are not detected easily. So millions of photons are needed to detect a signal. In radio waves quanta are so close in energy value that these waves are detected as continuous radiation. Hence, wave properties of radio waves predominates.

The emission or absorption of energy in steps may be extended to include any system like a mass oscillating on a spring. However, the energy steps are too much small to be detected.

Hence, the quantum effects are only important when observing atomic sized objects, where 'h' is a significant factor in any detectable energy change.

Electromagnetic Spectrum



Interaction Of Electromagnetic Radiation With Matter

Electromagnetic radiation or photons interact with matter in three distinct ways depends mainly on their energy.

The three processes are

(i) Photoelectric Effect

(ii) Compton Effect

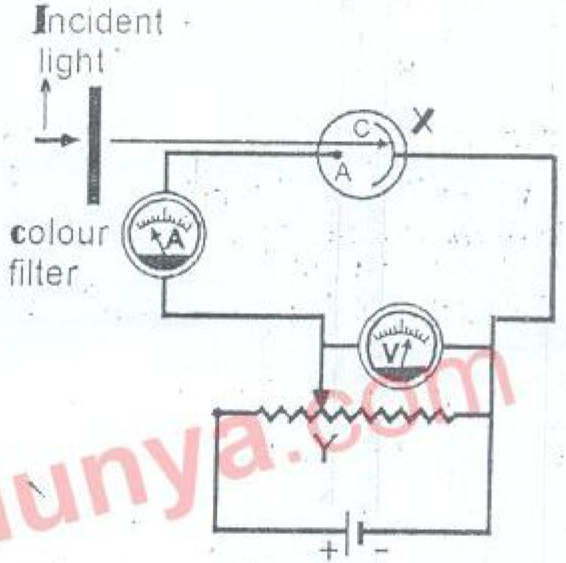
(iii) Pair Production.

Photoelectric Effect

The emission of electrons from a metal surface when exposed to light of suitable frequency is called the photoelectric effect. The emitted electrons are known as photoelectrons.

Experimental Arrangement

The photoelectric effect is demonstrated by the apparatus as shown in the figure.



The apparatus consists of an evacuated glass tube X which contains two electrodes A and C. The electrode A is connected with positive terminal of the battery, known as anode while electrode C is connected with negative terminal of the battery, known as cathode.

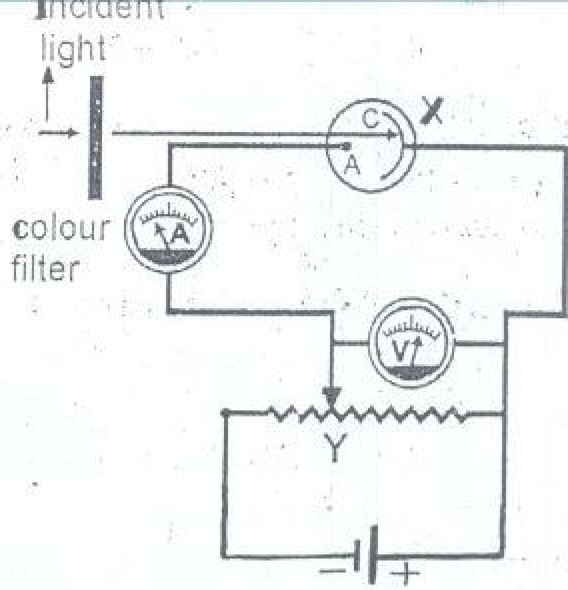
When monochromatic light from a source falls on the cathode C, it begins to emit electrons. The electrons emitted from the cathode are known as photoelectrons. These photo electrons are attracted by the positive anode A and the current starts flowing through the circuit which is measured by the ammeter. When light is cut off, then the current stops, which proves, that the current flows due to incident light, called photoelectric current.

Maximum Energy Of Photoelectrons

For maximum energy of photoelectrons, the battery terminals are reversed i-e; now anode A is at negative potential and cathode C is at positive potential.

In this condition the photoelectrons are repelled by the anode A and the photoelectric current decreases.

more and more negative, then at a certain potential, the photoelectric current becomes zero and no photoelectron will reach at anode A. This potential is called cut-off or stopping potential V_0. The electrons of maximum energy are not able to reach the collector plate A at this potential V_0. Hence, the stopping potential is the measure of maximum energy of photoelectrons.



If v_{max} is the maximum velocity of photoelectrons, then their maximum K.E. is given as

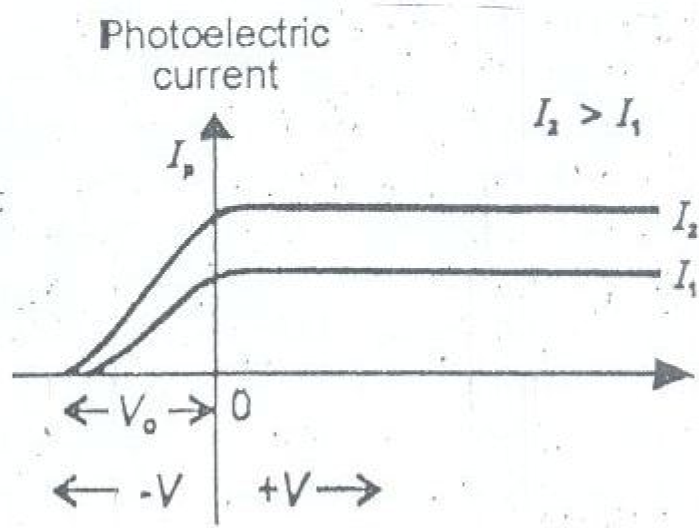
$$\text{Max. K.E.} = V_0 e$$

or $$\boxed{\frac{1}{2} m v_{max}^2 = V_0 e} \longrightarrow (1)$$

Where m is the mass of electron and e is the charge on electron.

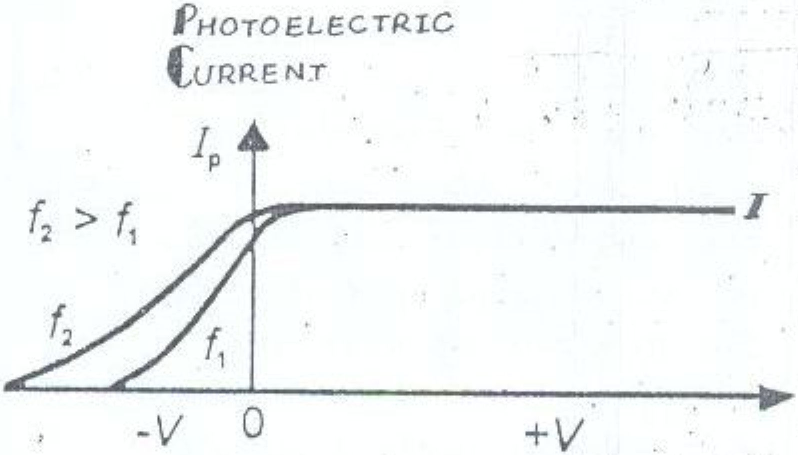
Dependance Of Photoelectric Current And Maximum K.E. Of Photoelectons

If the experiment is repeated with light beam of higher intensity, the amount of current increases but the current stops for the same value stopping potential V_0. The figure shows two curves of photoelectric current as a function of potential V where current $I_2 > I_1$.



This shows that photoelectric current depends upon the intensity of light and not on its frequency.

If the intensity of light is kept constant and the experiment is repeated with different frequencies of incident light, then we get the curves as shown.



The curves shows that the current is same and stopping potential is different for each frequency of incident light. Hence, the maximum K.E. of photoelectrons is directly proportional to the frequency of light 'f'.

EXPERIMENTAL RESULTS OF PHOTOELECTRIC EFFECT

The important results of experiment are

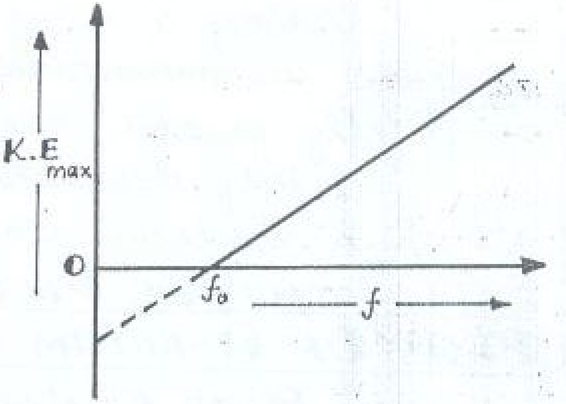
1. The electrons are emitted with different energies. the maximum energy of photoelectrons depends on the particular metal surface and the frequency of the incident light.

2. There is a minimum frequency, called Threshold frequency 'f_o' below which no electrons are emitted, however intense the light may be. This threshold frequency 'f_o' varies from metal to metal.

3. Electrons are emitted instantaneously from the metal surface if the frequency of incident light is greater than the threshold frequency and the intensity of light only determines their number.

4. The maximum energy of the photoelectrons increases with the increasing frequency above threshold frequency of the incident light.

A graph of the maximum kinetic energy of photoelectrons vs light frequency. Below a certain frequency i-e; threshold frequency 'f_o', no photo-emission occurs. ⟶



THRESHOLD FREQUENCY

The minimum frequency of incident light required to eject the electrons from the metal surface is called threshold frequency. It is denoted by f_o.

WORK FUNCTION

The minimum energy required to eject an electron from the metal surface is called work function. It is denoted by ϕ.

$$\boxed{\phi = hf_o}$$

Where f_o = Threshold frequency
h = Planck's constant

FAILURE OF ELECTROMAGNETIC WAVE THEORY OF LIGHT TO EXPLAIN PHOTOELECTRIC EFFECT

The experimental results of photoelectric effect could not be explained on the basis of electromagnetic wave theory of light. According to this theory, increasing the intensity of incident light should increase the K.E. of emitted electrons which contradicts the experimental result. Also, the classical electromagnetic wave theory cannot explain the threshold frequency of light.

This theory failed because it could not answer the following questions.

1. Why an intense beam of light fails to emit electrons from the metal surface when its frequency is slightly less than the threshold frequency of metal.

2. Why a weak beam of light ejects the electrons instantaneously when frequency of light is slightly greater than the threshold frequency.

3. Why there should be a threshold frequency at which electrons emission takes place.

Explanation Of Photoelectric Effect On The Basis Of Quantum Theory

Albert Einstein in 1905 extended the idea of quantization of energy proposed by Max Planck to explain photoelectric effect. According to quantum theory, light is emitted or absorbed discontinuously in packets or bundles of energy which are called quanta and known as photons. The energy of each photon is directly proportional to the frequency 'f' of light as

$$E \propto f$$

or $$\boxed{E = hf}$$

Einstein's Explanation

According to Einstein, a beam of light of frequency 'f' consists of a stream of energy corpuscles, called photons. The energy of each photon is 'hf'. A photon may be absorbed by a single electron in the metal surface. The electron needs a certain minimum energy equal to the work function $\phi = hf_o$ of the metal surface to escape from the metal surface. If the energy of the incident photon is sufficient, then the electron ejected from the metal surface instantaneously. A part of the photon energy equal to work function of the metal surface is used to eject the electron from the metal surface and remaining appear as K.E. of the electron.

Einstein's Photoelectric Equation

If a photon of energy 'hf' greater than the work function 'ϕ' of the metal surface falls upon it, then the photon transfers the whole energy to the electron of the metal surface. A part of this energy equal to the work function is used to eject the electron from the metal surface and the remaining energy appear as the K.E. of the electron. So, we can write as

$$\begin{pmatrix}\text{Incident Photon} \\ \text{Energy}\end{pmatrix} - \begin{pmatrix}\text{Work} \\ \text{Function}\end{pmatrix} = \begin{pmatrix}\text{Maximum K.E.} \\ \text{of Photoelectron}\end{pmatrix}$$

or

$$\boxed{hf - \phi = \frac{1}{2} m v_{max}^2} \longrightarrow ②$$

This is known as <u>Einstein's Photoelectric Equation</u>.

When max. K.E. of photoelectron is zero, then the frequency 'f' of incident light is equal to the threshold frequency 'f_o', then equation ② becomes as

$$hf_o - \phi = 0 \qquad \left(\because \frac{1}{2} m v_{max}^2 = 0\right)$$

or

$$\phi = hf_o$$

Put $\phi = hf_o$ in equation ②, we get

$$hf - hf_o = \frac{1}{2} m v_{max}^2$$

or

$$\frac{1}{2} m v_{max}^2 = hf - hf_o$$

or

$$\boxed{(K.E.)_{max} = hf - hf_o} \longrightarrow ③$$

This equation holds good only for those electrons which comes out of the metal surface with full surplus energy.

It should be noted that all the emitted electrons do not possess the maximum K.E. Some electrons come straight out of the metal surface and some lose energy in atomic collisions before coming out.

Albert Einstein was awarded Nobel prize in physics in 1921 for his explanation of photoelectric effect.

<u>**NOTE**</u>

Photoelectric effect cannot be explained if we assume that light consists of waves and energy is uniformly distributed over its wavefront.

It can only be explained by assuming light consists of corpuscles of energy known as photon. <u>Hence, photoelectric effect shows the corpuscular or particle nature of light.</u>

PHOTOCELL

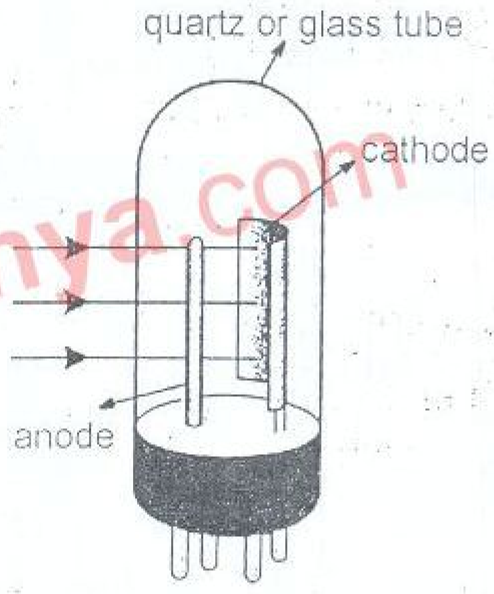
A device which converts light energy into electrical energy, called a photocell.

PRINCIPLE

The working principle of photocell is based on photoelectric effect.

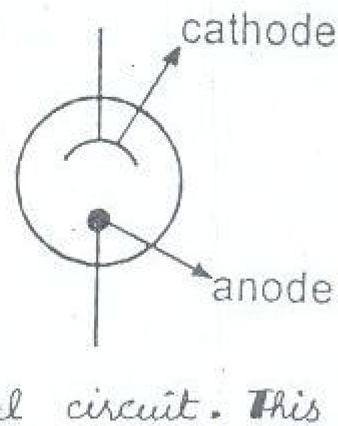
CONSTRUCTION

It consists of an evacuated glass bulb with a thin anode rod and a cathode of some suitable metal surface. The material of the cathode is selected to suit to the frequency range of incident light over which the cell is operated. For example, sodium or potassium cathode emits electrons for visible light and cesium coated oxidized silver emits electrons for infra-red light and some other metals emits electrons for ultra-violet radiation.



WORKING

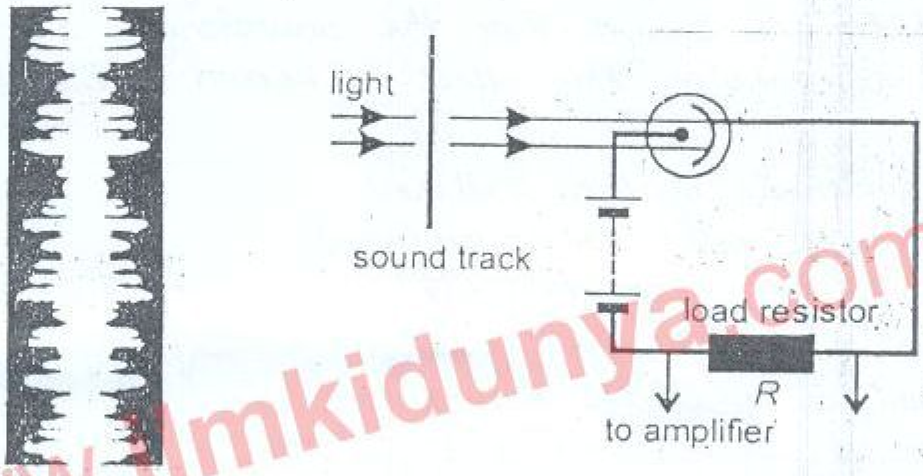
When light of certain suitable frequency incident on cathode plate, electrons are emitted and a current flows in the external circuit. This current increases with the increase in intensity of light. The current stops when the incident light is interrupted.



Applications Of Photocell

Photocell has wide range of applications which are given as

1. Security systems
2. Counting systems
3. Automatic door systems
4. Automatic street lighting
5. Exposure meter for photography
6. Sound track of movies as shown in figure.



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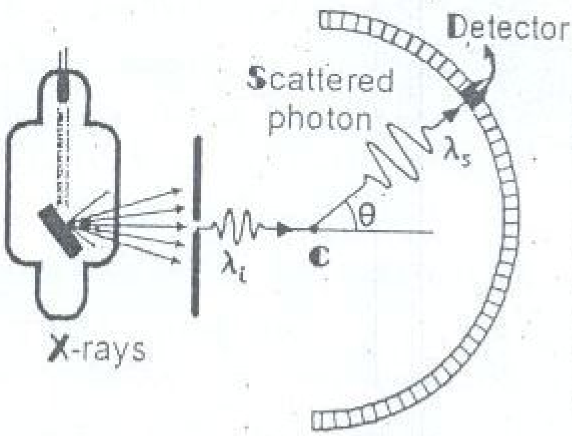
Compton Effect

Arthur Holly Compton in 1923 at Washington University studied the scattering of X-ray photons by loosely bound electrons from a graphite target as shown in figure.



Statement

The phenomenon in which the wavelength 'λ_s' of the scattered X-ray photons is larger than the wavelength 'λ_i' of the incident X-ray photons is known as Compton effect.

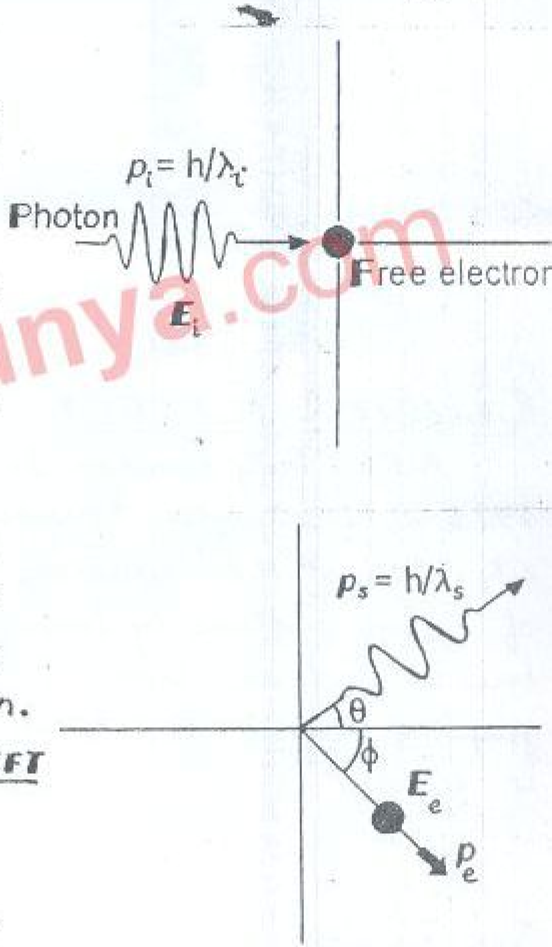
OR

The phenomenon in which an incident photon of frequency 'f_i' is scattered by an electron and the scattered photon has a frequency $f_s < f_i$ is called Compton effect.

EXPLANATION

A.H. Compton measured the wavelength of X-rays scattered at an angle 'θ' with the original direction. He found that wavelength λ_s of the scattered photon is larger than the wavelength λ_i of the incident X-ray photon. This effect is known as Compton effect.

The increase in wavelength of the scattered X-rays could not be explained on the basis of classical electromagnetic wave theory. Compton suggested that X-rays consists of photons and in the process of scattering, the photons collide with the electrons like billiard balls as shown in figures. In this collision, a part of incident photon energy and momentum is transferred to an electron.



COMPTON OR WAVELENGTH SHIFT

Applying laws of conservation of energy and momentum to the process, he find an expression for the change in wavelength $\Delta\lambda$, known as Compton shift or wavelength shift for scattering angle θ given as

$$\boxed{\Delta\lambda = \frac{h}{m_o c}(1 - \cos\theta)} \longrightarrow (1)$$

Where m_o = Rest mass of the electron = 9.1×10^{-31}

C = Speed of light $= 3.0 \times 10^{8}\ m.s^{-1}$
h = Planck's constant $= 6.63 \times 10^{-34}\ J.s$

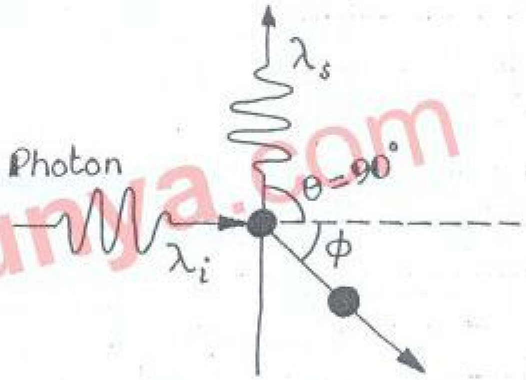
The factor h/m_oC has dimensions of length and is called Compton wavelength and its numerical value is given as

$$\boxed{\frac{h}{m_oC} = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 3.0 \times 10^{8}} = 2.43 \times 10^{-12}\ m}$$

Maximum Compton Shift

If the scattered X-ray photons are observed at $\theta = 90°$, then the Compton shift $\Delta\lambda$ equals to the Compton wavelength which is the maximum Compton shift given as below

Put $\theta = 90°$ in eq. (1)



$$\Delta\lambda = \frac{h}{m_oC}(1 - \cos 90°)$$

or $$\Delta\lambda = \frac{h}{m_oC}(1 - 0)$$

or $$\boxed{\Delta\lambda = \frac{h}{m_oC}}$$

Hence, Compton shift is equal to the Compton wavelength at $\theta = 90°$.

NOTE

⇒ A.H. Compton was awarded Nobel prize in Physics in 1927 for his discovery of Compton effect.

⇒ Equation (1) was found to be in complete agreement with Compton's experimental result which is the confirmation of particle like interaction of electromagnetic waves with matter.

⇒ If photon is scattered at an angle $\theta = 180°$ i-e; photon bounces back after scattering, then Compton shift $\Delta\lambda$ is

$$\Delta\lambda = \frac{h}{m_oC}(1 - \cos 180°) = \frac{h}{m_oC}(1 - (-1))$$

or $$\boxed{\Delta\lambda = 2\left(\frac{h}{m_oC}\right) = 2 \times \text{Compton Wavelength}}$$

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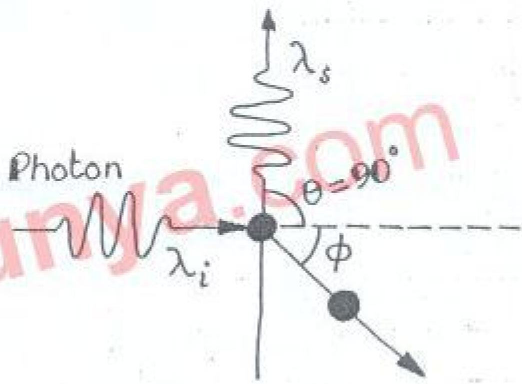

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Materialization Of Energy

The creation of two particles i-e; electron and positron with equal and opposite charges is essential for charge conservation in the universe. The positron is also known anti-particle of electron or anti-electron. In order to conserve the momentum and energy, the pair production take place in the electric field in the vicinity of a heavy nucleus.

In this process, the energy is converted into matter according to Einstein's equation $E = mc^2$. Hence, this process is also known as materialization of energy.

Minimum Energy For Pair Production

The minimum energy required for γ-ray photon to disintegrate into electron-positron pair is $2m_oc^2$, where m_oc^2 is the rest mass energy of electron or positron.

The numerical value of m_oc^2 is

$$m_oc^2 = 9.1 \times 10^{-31} \times (3.0 \times 10^8)^2$$

or $$m_oc^2 = 8.19 \times 10^{-14}\ J$$

or $$m_oc^2 = \frac{8.19 \times 10^{-14}}{1.6 \times 10^{-19} \times 10^6}\ MeV = 0.511\ MeV$$

Now, minimum energy for pair production is

$$2m_oc^2 = 2 \times 0.511\ MeV$$

or $$\boxed{2m_oc^2 = 1.02\ MeV}$$

So, minimum energy required to create an electron-positron pair is $2m_oc^2 = 1.02\ MeV$

Pair Production Equation

If energy of γ-ray photon is greater than $2m_oc^2$, then energy equal to $2m_oc^2 = 1.02\,MeV$ will be used to produce electron-positron pair and remaining energy will be appeared as kinetic energies of electron and positron. So, the pair production process can be represented by equation as

Energy of Photon = [Energy required for pair production] + [Kinetic energy of the particles]

or $$\boxed{hf = 2m_oc^2 + K.E.(e^-) + K.E.(e^+)}$$

This equation is known as '<u>Pair Production Equation</u>'.

CONDITIONS FOR PAIR PRODUCTION

The following are the conditions for pair production

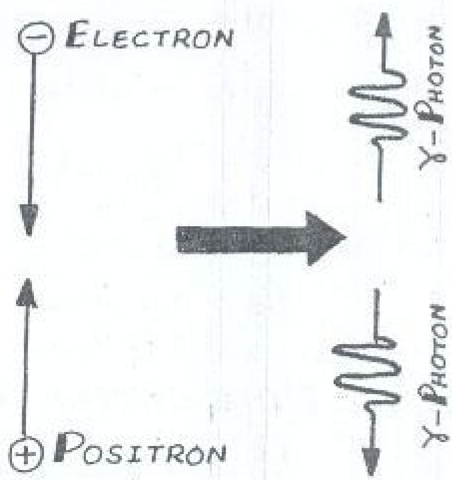
1. The charge, mass and energy should be conserved.
2. The two particles must be emitted in opposite directions so that total momentum is conserved.
3. The γ-ray photon must be incident on a heavy nucleus, so that energy and momentum is conserved.
4. The energy of γ-ray photon to create an electron-positron pair must be $2m_oc^2 = 1.02\,MeV$.

ANNIHILATION OF MATTER

It is the reverse process of pair production. When a positron comes close to an electron, they destroy or annihilate each other and produce two γ-ray photons. This process is called annihilation of matter.

EXPLANATION

When an electron and positron destroy or annihilate each other, then the mass of these two particles appear as two γ-ray photons i-e;



$$\boxed{e^- + e^+ \longrightarrow \gamma + \gamma}$$

CONDITIONS

The following are the conditions for annihilation of matter

1. The two photons are produced travelling in opposite directions, so that momentum

is conserved.

2. To annihilate electron and positron each other, 1.02 MeV energy must be required.
3. The charge, mass and energy should be conserved.
4. Each photon has energy 0.51 MeV equivalent to rest mass energy of electron or positron.

ANTI-MATTER

The existance of positron shows the existance of anti-matter in the universe. The existance of positron was predicted by DIRAC in 1928 and it was discovered in the cosmic radiation in 1932 by CARL ANDERSON. Gradually, it became clear that every particle has a corresponding anti-particle with the same mass and charge but of opposite sign.

Particles and anti-particles also differ in the signs of other quantum numbers. A particle and its anti-particle cannot exist together at one place. Whenever they meet, they annihilate each other, that is, the particles disappear and their combined rest energies appear in other forms. Proton and anti-proton annihilation has also been observed at Lawrence Barkeley Laboratory.

WAVE NATURE OF PARTICLES OR de-BROGLIE HYPOTHESIS

It has been observed that light displays a dual nature, that is, it acts as a wave and as a particle.

In 1924, a French physicist, Louis de-Broglie thought that if wave can behave as particles, then perhaps particles can behave as waves under certain circumstances. As momentum of a photon is given as

$$P = h/\lambda$$

de-Broglie suggested that if a particle of mass 'm' moving with velocity 'v' can behave as a wave, then the momentum of particle should be same as

$$P = h/\lambda \longrightarrow (1)$$

Also momentum of a particle is

$$P = mv \longrightarrow (2)$$

Comparing equation (1) and (2)

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

or

$$\boxed{\lambda = \frac{h}{mv}} \longrightarrow (3)$$

This equation is called **de-Broglie relation**. Here 'λ' is the wavelength associated with particle waves and the wave associated with particles, called particle wave or **de-Broglie's wave**. Hence an electron can be considered to be a particle and it can also be considered as a wave.

EXAMPLES

1. A rifle bullet of mass 20g and moving with speed of 330 m.s^{-1} will have a wavelength 'λ' as

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

Where

$$m = 20g = 20 \times 10^{-3} kg = 2 \times 10^{-2} kg$$
$$v = 330 m.s^{-1}$$
$$h = 6.63 \times 10^{-34} J.s$$

$$\therefore \quad \lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{2 \times 10^{-2} \times 330} = 1 \times 10^{-34} m$$

This wavelength is so small that it cannot be detected. Hence, an object of large mass moving with ordinary speed has a very small wavelength that its wave effects such as interference and diffraction are negligible.

2. An electron moving with a speed of 1×10^{6} m.s^{-1} will have a wavelength 'λ' as

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

Where

$$m = 9.1 \times 10^{-31} kg$$
$$v = 1 \times 10^{6} m.s^{-1}$$

$$\therefore \qquad \lambda = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 1 \times 10^{6}}$$

$$\text{or} \qquad \lambda = 7 \times 10^{-10}\,m$$

This wavelength is in the X-rays range and can be measured. Hence, for an electron wave effects such as interference or diffraction are measureable.

CONCLUSION

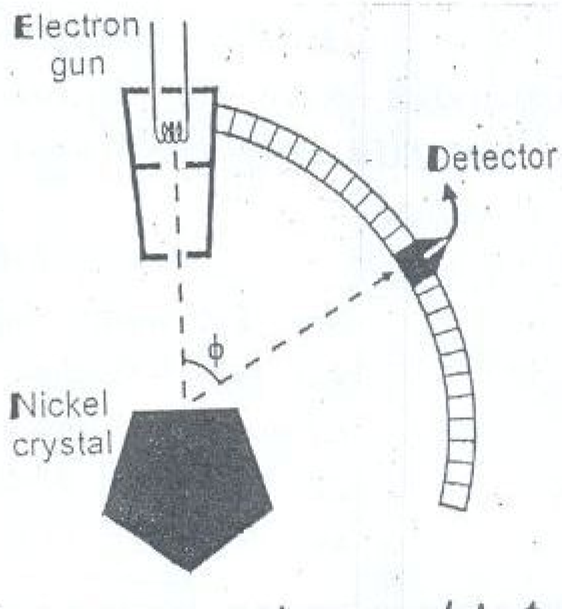
The above examples conclude that objects having small masses like electron, proton, neutron etc having relativistic speeds can behave as waves.

DAVISSON AND GERMER EXPERIMENT

The first experimental evidence for de-Broglie hypothesis, that is, wave nature of particles was provided by two American scientists, CLINTON J. DAVISSON and LASTER H. GERMER in 1926. They showed that the electrons are diffracted from metal crystals in exactly the same way as X-rays or any other wave diffraction from crystals.

CONSTRUCTION AND WORKING

The apparatus used by Davisson and Germer is shown in the figure.



In this experiment, electrons emitted from a heated filament were accelerated through an adjustable applied voltage V. The accelerated beam of electrons of energy 'Ve' is made to fall on a nickel crystal. The electrons beam diffracted from nickel crystal surface enters a detector and is recorded as a current I. The gain in K.E. of the electron as it is accelerated by a potential V in the electron gun is given as

$$K.E. = \text{Electron Energy}$$

or $$\frac{1}{2}mv^2 = Ve$$

or $$mv^2 = 2Ve$$

or $$m^2v^2 = 2mVe$$

or $$mv = \sqrt{2mVe} \longrightarrow (1)$$

Where,
m = Mass of electron = 9.1×10^{-31} kg
v = Speed of electron
e = Charge on electron = 1.6×10^{-19} C

According to de-Broglie equation, we have

$$\lambda = \frac{h}{mv} \quad \left[\begin{array}{l}\text{Put value of } mv \\ \text{from equation } (1)\end{array}\right]$$

or $$\lambda = \frac{h}{\sqrt{2mVe}}$$

In one of the experiments, the accelerating voltage $V = 54$ volts, hence

$$\lambda = \frac{h}{\sqrt{2mVe}} = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 54 \times 1.6 \times 10^{-19}}}$$

or $$\boxed{\lambda = 1.66 \times 10^{-10} m} \longrightarrow (2)$$

In this experiment, most of the electrons were diffracted from the crystal surface for a glancing angle of 65°. According to Bragg's equation for X-ray diffraction, we have

$$m\lambda = 2d \sin\theta$$

For 1st order diffraction, $m = 1$
For nickel, Grating element = $d = 0.91 \times 10^{-10}$ m
Glancing angle $\longrightarrow = \theta = 65°$

$\therefore$ $$1 \times \lambda = 2 \times 0.91 \times 10^{-10} \times \sin 65°$$

or $$\lambda = 2 \times 0.91 \times 10^{-10} \times 0.852$$

or $$\boxed{\lambda = 1.65 \times 10^{-10} m} \longrightarrow (3)$$

QUESTIONS

19.1. *What are the measurements on which two observers in relative motion will always agree upon?*

Ans. The force and acceleration measurements for the two observes are same , when these are in frames of reference. Moving with uniform velocity w.r.t. each other (inertial frames).

19.2. *Does the dilation mean that time really passes more slowly in moving system or that it only seems to pass more slowly?*

Ans. Time dilation means that according to theory of relativity observer can say that moving clocks appears to run slow. So time dilation is apparent change and it not the actual change.

19.3. *If you are moving in a spaceship at a very high speed relative to the Earth, would you notice a difference (a) in your pulse rate b of people on Earth?*

Ans. The pulse rate of the person . Who's is travelling in a space ship is not changed w.r.t clock inside the space ship. But he will experience the change in pulse rate of people on Earth, because the clock on which he is going to measure the pulse rate moves w.r.t. Earth at large velocity.

19.4. *If the speed of light were infinite, what would the equations of special theory of relativity reduce to?*

Ans. If we take $C \to \infty$ then equations of special relativity become as given below.

$$m = \frac{m_o}{\sqrt{1-\frac{V^2}{C^2}}} = m_o \text{ ----------- as } \frac{V^2}{C^2} \to o$$

$$l = l_o\sqrt{1-\frac{V^2}{C^2}} = l \text{ ----------- as } \frac{V^2}{C^2} \to o$$

$$E = mc^2 = \infty \text{ as } C \to \infty$$

19.5. *Since mass is a form of energy, can we conclude that a compressed spring has more mass than the same spring when it is not compressed?*

Ans. According to theory of special relativity the variation of mass is due to motion and not due to position. As the compressed spring does not move os there is no change in its mass. There is change of its P.E. only.

19.6. *As a solid is heated and begins to glow, why does it first appear red?*

Ans. The solid when heated then at the start of its glow it appears red. Because at the start of beginning of its glow. It emits wavelength of red light radiation.

19.7. *What happens to total radiation from a blackbody if its absolute temperature is doubled?*

Ans. The total radiation intensity 'E' is directly proportional to 4^{th} power of its Kelvin's temperature. It is according to Stephen's law.

According to this law, when the temperature is increased to double of its value, then value of 'E' increases $(2)^4 = 16$ or It becomes 16 times greater.

19.8. *A beam of red light and a beam of blue light have exactly the same energy. Which beam contains the greater number of photons?*

Ans. Red light has less frequency then blue light. Therefore, the two colour beams having same energy will contain different number of photons. The less number of photons are present in blue light beam because it consists of photons of large frequency, as compared with red light beam and, so, each photon contain larger energy then red light photon.

19.9. *Which photon, red, green, or blue carries the most (a) energy and momentum (b)?*

Ans. (a) The photons of blue light have large frequency value so ($E = hf$) these must have the largest value of energy as compared with photons of red and green colour light.

(b) The wavelength λ is inversely proportional to frequency or $\lambda \propto \frac{1}{f}$ hence wavelength of blue light is greatest than red or green. As formula for momentum is

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

This shows that for smallest value of λ, the momentum is largest. This proves that blue light photons have largest values of momentum than red / green.

19.10., *Which has the lower energy quanta? Radio waves or X-rays.*

Ans. The frequency of radio waves is very small as compared with x-rays. Therefore, quanta of radio waves have less energy than quanta of x –rays.

19.11. *Does the brightness of a beam of light primarily depends on the frequency of photons or on the number of photons?*

Ans. The brightness means intensity, which depends primarily on the number of photons present in the beam.

19.12. *When ultraviolet light falls on certain dyes, visible light is emitted. Why does this not happen when infrared light falls on these dyes.*

Ans. The ultraviolet light contain photons of high energy. These are able to excite the atoms of dyes, which during their de-excitation can emit frequencies, which are detectable by normal human eye.

But when infra red radiations are made incident upon the atoms of dyes then these may be excited but, now, the dexcitation energy is such that photons of frequencies are emitted whose value lie below the least value of frequency of visible spectrum, so these cannot be detected by normal eye.

19.13. *Will bright light eject more electrons from a metal surface than dimmer light of the same colour.*

Ans. The light of same colour can eject more electrons from metal surface when it is bright (intense) because it contains large number of photons, as compared with dimmer light of same frequency.

19.14. *Will higher frequency light eject greater number of electrons than low frequency light?*

Ans The higher frequency light can eject electrons of large K.E. as compared with lower frequency light, when intensities of the two are same. Because higher frequency photon has large value of energy and (K.E.) departed to photoele[illegible] is large.

19.15. *When light shines on a surface, is momentum transferred to the metal surface?*

Ans. As a rough estimation about 20% incident light energy is absorbed in each reflection. This energy is absorbed by the reflecting surface. This makes clear that momentum is also transferred from the incident light to the reflecting surface. All though this transfer is so small in amount to make any disturbance in the reflecting surface.

19.16. *Why can red light be used in a photographic dark room when developing films, but a blue or white light cannot?*

Ans. The photons of red light in visible spectrums have less energy than for blue or white light. Therefore photographic films and the material concerned are less effected, in the presence of red light. Hence red light is preferred in photographic dark light is preferred in photographic dark rooms.

19.17. *Photon A has twice the energy of photon B. what is the ratio of the momentum of A to that of B?*

Ans. The formula for momentum of photon is

$$P = \frac{E}{c} \quad \text{where } E = hf$$

$$P = \frac{hf}{c}$$

Momentum of photon A $= P_A = \frac{hf_a}{c}$

Momentum of photon A $= P_B = \frac{hf_B}{c}$ ------ (1)

As $f_A = 2f_B$

Therefore $P_A = \frac{2hf_B}{c}$ ------- (2)

Dividing equations (1) and (2) we get

$$\frac{P_B}{P_A} = \frac{\frac{hf_B}{c}}{\frac{2hf_B}{c}}$$

$$\frac{P_B}{P_A} = \frac{1}{2}$$

or $P_B = P_A = 1 : 2$

19.18. *Why don't we observe a Compton effect with visible light?*

Ans. Visible light photons are of smaller energy and momentum than x – ray. Their penetrating power is almost negligible. So these are unable to show Compton's effect.

19.19. *Can pair production take place in vacuum? Explain?*

Ans. For pair production law of conservation of momentum requires that same heavy nucleus should be present near the spot of pair production. This heavy nucleus helps the two antiparticles in opposite directions. In vacuum it could not be possible. So pair production cannot take place in vacuum.

19.20. *Is it possible to create a single electron from energy? Explain?*

Ans. The transfer of energy into mass requires the production so two particles which act as antiparticle for each other. So that when there recombine together then their mass is totally converted into energy , again. Hence single particle (without its antiparticle) cannot be created from energy.

19.21. *If electrons behaved only like particles, what pattern would you expect on the screen after the electrons pass through the double slit?*

Ans. When electrons have particle like properties only, then these would pass through the slits straight and fall on the screen just in front of the slits to give exact images of the double slit on the screen.

19.22. *If an electron and a proton have the same de Broglie wavelength, which particle has greater speed?*

Ans. The mass of proton is greater than mass of electron. If their energies are such both of these have same value of de Broglie's wavelength. Then we can use formula.

$$\lambda = \frac{h}{mv} \text{ and } \lambda_p = \lambda_e$$

This shows that for large mass (m) the velocity (v) most be small. Hence proton of large mass moves with lesser velocity than electron.

19.23. *We do not notice the de Broglie wavelength for a pitched cricket ball. Explain why?*

Ans. According to de – Broglie's relation

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

For particles of large mass (like pitched) cricket ball) the value of wavelength 'λ' becomes so small that it cannot show wave characteristics and cannot be noticed.

19.24. *If the following particles all have the same energy, which has the shortest wavelength? Electrons, neutron, proton.*

Ans. The K.E. of a moving particle is given by K.E. $= \frac{1}{2}mv^2$

Or $\quad K.E. = \frac{m^2v^2}{2m}$

$$K.E. = \frac{P^2}{2m}$$

This relation shows that if (K.E.) of electron, proton, neutron and alpha particle is same, then for particle of small mass, the linear momentum is also small ($P^2 \propto 2m$) and for small value of 'P' λ, is large, according to formula

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

This proves that electron has largest value of wavelength for smallest momentum as compared with other particles. And alpha particle of largest mass has, largest momentum and shortest wavelength. (because its momentum is large).

19.25. *When does light behave as a wave? When does it behave as a particle?*

Ans. The interference, diffraction polarization properties of light confirm wave behaviour of light, when as photoelectric effect, and Compton's effect show the particle nature of particle.

19.26. *What advantages an electron microscope has over an optical microscope?*

Ans. In electron microscope fast moving electrons are used to produce detailed image. The wavelength of electrons is very small so its resolving power is very large. It can resolute a distance of 0.5nm to 1nm whereas optical microscope has the resolving power = 0.2 m. This is the major advantage of electron microscope over optical microscope.

Moreover, the picture of internal structure of an object can also be obtained whereas optical microscope can not do so.

19.27. *Measurements show a precise position for an electron, can those measurements show precise momentum also? Explain?*

Ans. The less is uncertainty in the measurement of position of a particle (or more precise is position measurement) the uncertainty in the measurement of momentum is large, according to uncertainty relation given by Heisenberg.

So it is not possible to have more precise measurement of momentum when its position is measured precisely.