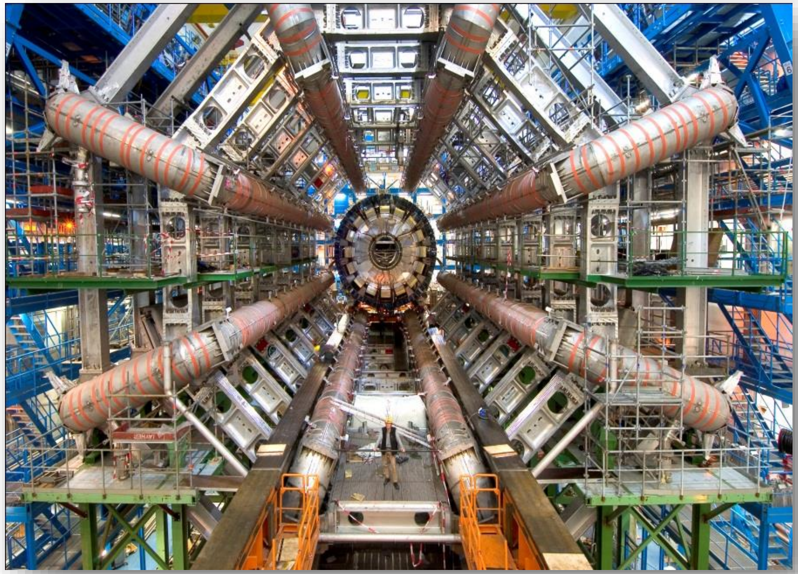
PART-I

QUANTUM PHYSICS

Quantum physics is an exceedingly complex and theoretical field, usually described only with the help of advanced math. Nobel-prize winning physicist **Richard Feynman** alleged with confidence that there was "nobody" who really understood quantum physics.

Recent happenings in Quantum physics



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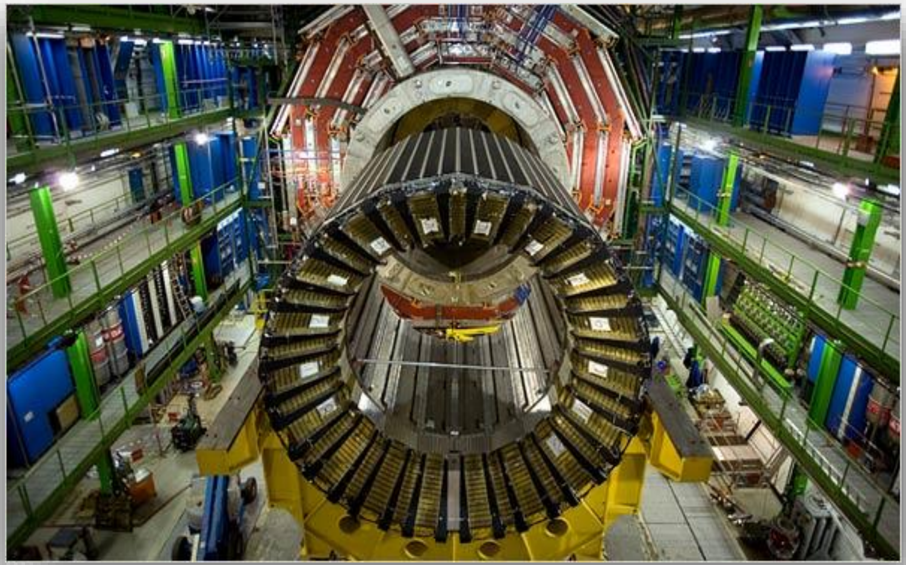

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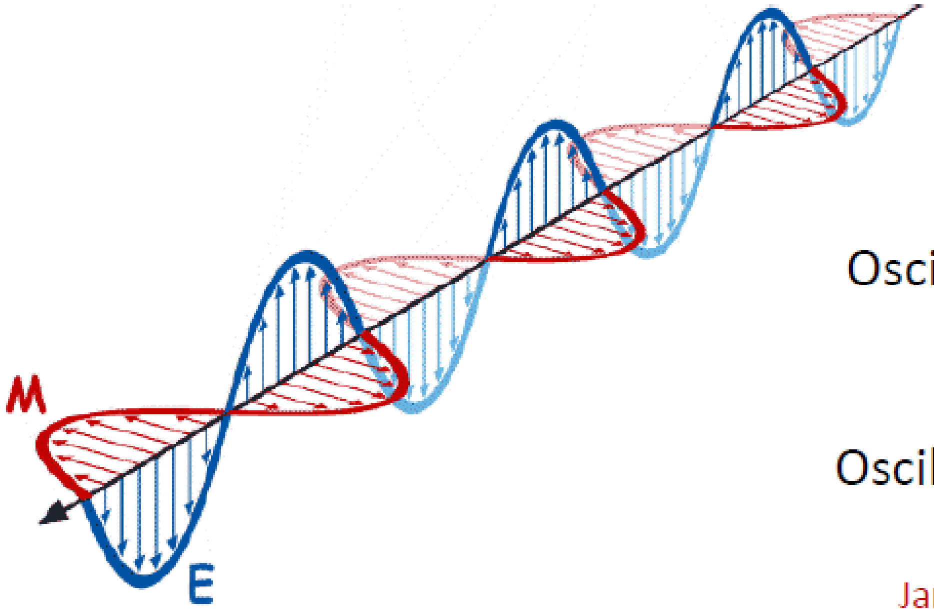
(1) The Large Hadron Collider (LHC) at the CERN facility.

(2) The actual machine, built in a circular tunnel the earth, is about 27 kilometers (16.8 miles) long. The LHC will help us test quantum theories that could not be tested before.

The classical description of light

Light, X-rays, microwaves, radio waves, are all examples of *ELECTROMAGNETIC RADIATION:*



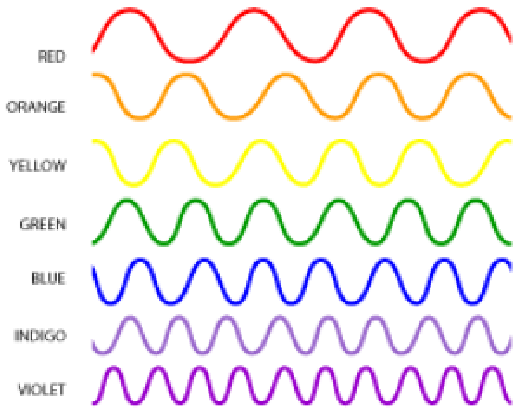
Oscillating electric field

Oscillating magnetic field

James Clerk Maxwell 1864

Properties of Light

Colour: determined by wavelength

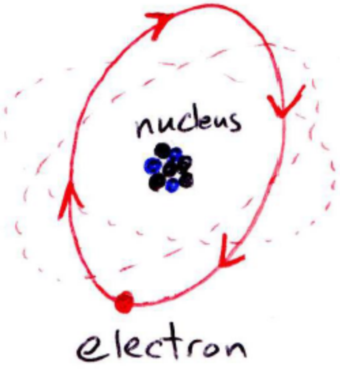


Intensity: determined by amplitude

Light carries energy

Energy ⟷ Intensity ⟷ Amplitude Squared

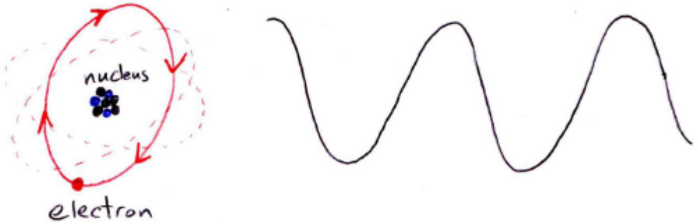
Failures of classical physics I



"Planetary" picture of atom:

Electrons orbiting around nucleus

Sounds okay, but...



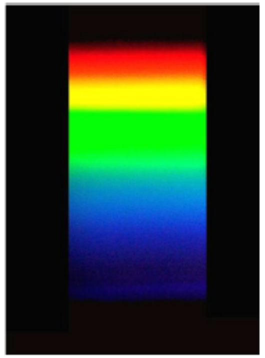
Orbiting charge would produce EM radiation

This carries away energy

Electron losing energy spirals into nucleus

All matter as we know it ceases to exist in 10^{-10}s.

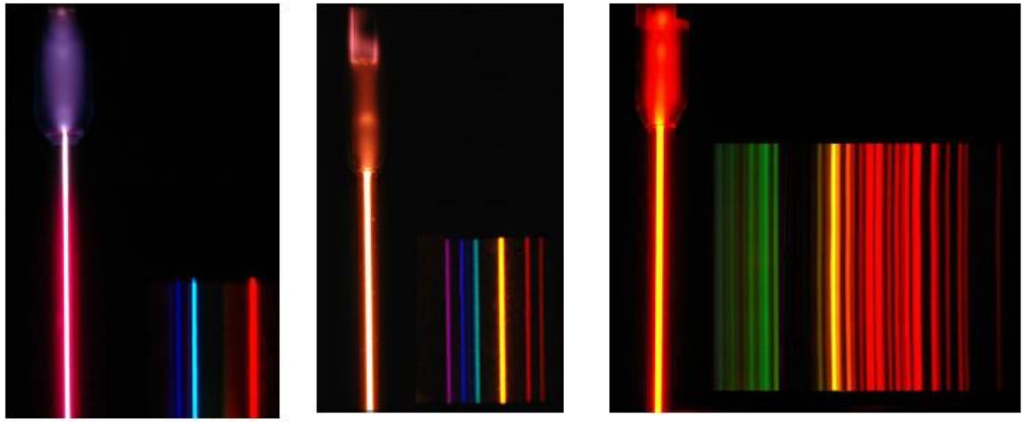
Failures of classical physics II



Light from any source is a combination of wavelengths and intensities.

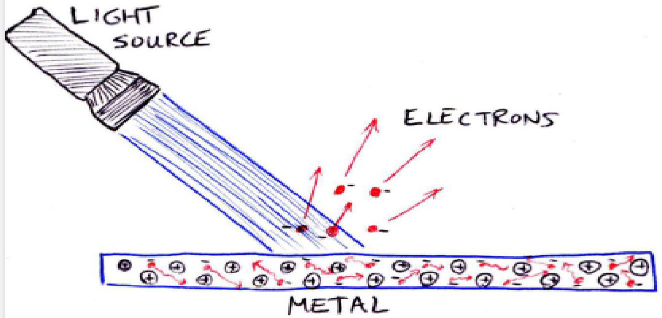
19th century physicists completely failed to explain observed spectrum of light from hot objects

Even more mysterious: spectrum of light from gases of pure elements



Hydrogen Helium Neon

The photoelectric effect: explained



Electrons trapped in metal (attracted to positive nuclei)

Can free them if we provide enough energy

Energy carried by light can be transferred to electrons

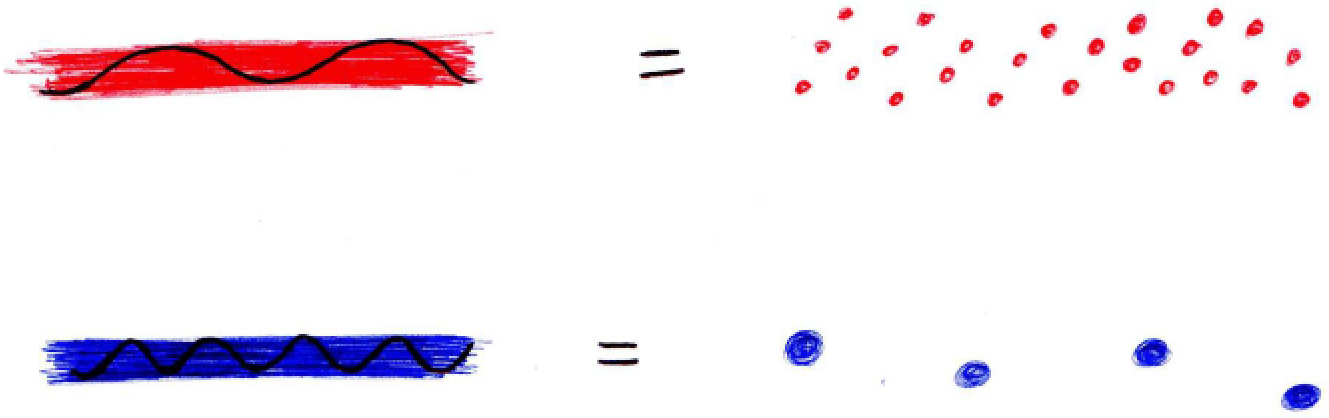
BUT: we only see the effect for certain colours!?

Very intense red light: No electrons

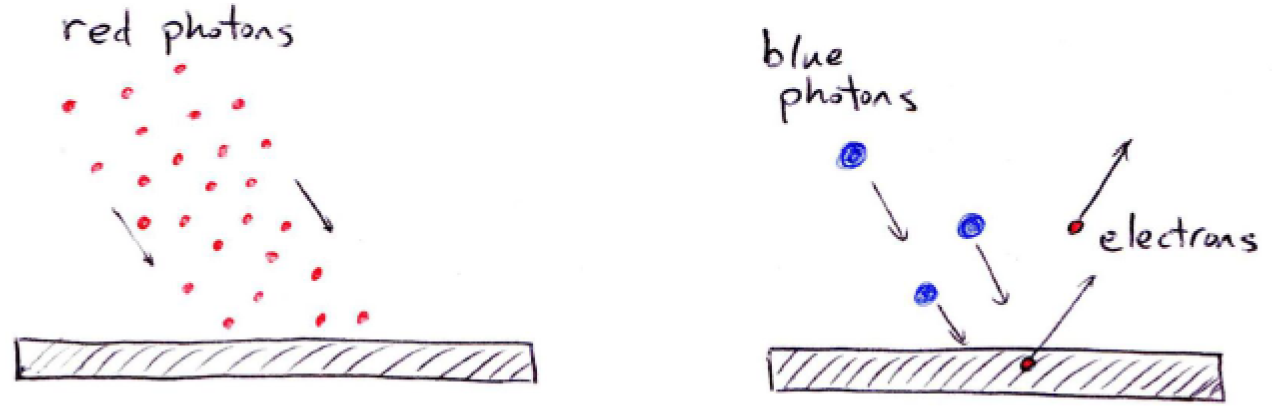
Feeble blue light: Electrons emitted

Einstein to the Rescue

Einstein's idea: light made of "photons" =lumps with energy inversely proportional to wavelength



Einstein's explanation



Electrons can only absorb energy from individual photons

Only light with short enough wavelength has photons with enough energy to eject an electron

Einstein’s Only Nobel Prize

Quantitative prediction (1905): maximum kinetic energy of ejected electrons increases linearly with inverse of wavelength (photon energy)

Experimental verification by Milliakan in 1915

Nobel prize for Einstein in 1921

Difficulties with Classical Physics

1. It could not explain the ***motion of the microscopic bodies*** like atoms, electrons protons etc. which move with the relativistic speeds.
2. It could not ***explain stability of atoms***. Acc. To classical electromagnetic theory atom must collapse but atom is a stable system.
3. It could not ***explain line spectra*** i.e. emission of radiations of some particular wavelengths and not of all wavelengths.
4. It could not explain ***variation of specific heat of solids with temperature, emission of X-rays*** etc.
5. It could not explain ***Photoelectric effect***.

6. The classical ideas failed to explain the distribution of energy in ***black body radiation spectrum***.
7. It could not explain the phenomena connected with the ***spin of particles*** and ***Pauli exclusion principle.***
8. ***Compton effect, Raman effect, Radioactivity, scattering phenomena*** are not explained by classical theory.
9. It could not explain ***dispersion of light***.

The difficulties faced by classical physics led the scientists to abandon classical ideas and search new ideas.

Quantum Physics came into existence after **Plank's *hypothesis***.

WHAT IS QUANTUM?

IN LATIN IT MEANS ***DISCREATE QUANTITY***

The quantities can be momentum, energy etc.

Two stages of quantum mechanics:

Max Plank hypothesis (1900): radiations are emitted or absorbed by matter in discrete packets/ quantas.

W. Heisenberg (1925) & E. Schrödinger (1926): The variables like momentum and energy were found to have discrete and discontinuous values.

Wave particle duality

Matter has particle properties and under suitable conditions, it also has wave properties.

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

For large object: wavelength is so small that cannot be observed

For electrons wave properties become significant.

The amount of energy of each quanta is

$$E = h\nu$$

Classical vs Quantum world

In everyday life,
quantum effects
can be safely
ignored

At atomic & subatomic scales,
quantum effects
are dominant & must be
considered

This is because
Planck's constant is so
small

Laws of nature
developed without
consideration of
quantum effects do not work
for atoms

Classical vs Quantum world

Classical	Quantum
Deals with the objects of macroscopic size	Deals with the objects of microscopic size
Newtonian Physics, it has been developed on the basis of Newton's law of motion F=m.a	Laws of motion are based on Schrodinger wave equation $[\frac{-\hbar^2}{2m}\nabla^2 + V]\,\psi = i\hbar\frac{\partial\psi}{\partial t}$
Deals with the certainties	Deals with the probabilities
Future behavior can be predicted If the initial position and momentum are known	Uncertainty in finding the initial position and momentum as given by Heisenberg Uncertainty principle

Planks Quantum hypothesis

The hypothesis that energy is emitted or absorbed in a discrete manner in the form of quanta is called *Plank's* quantum hypothesis.

$$E = nhv$$

n= 1,2,3,…..any positive integer, defines as energy state

h= frequency of oscillations

v= Plank's constant (***6.63 X 10^{-34} Joule-sec***)

classical mechanics failed to explain

1. Relativistic motion of sub-atomic particles.
2. Stability of an atom
3. Spectral series of Hydrogen atom
3. Black body radiation

Max Planck in 1900 at a meeting of German Physical Society read his paper "**On the theory of the Energy distribution law of the Normal Spectrum**". This was the start of the revolution of Physics i.e. the start of **Quantum Mechanics**.

The first stage began with max Plank's hypothesis (14 Dec.'1900) according to that radiation is **emitted and absorbed by matter in discrete packets**. Each quantum has energy, h*v*, where *v* is frequency of radiations.

The second stage began with the concepts of W. Heisenberg (1925) and E. Schrodinger (1926). The variable like **energy, momentum, now, were found to have discrete quantity**.

The particle has definite **position, size, mass velocity, momentum, energy and its motion** is described by **Newton's Law of motion**.

A Wave possesses **wavelength, amplitude, frequency**. It can transport energy without transport of matter. It cannot be localized and extends in space.

It is a generalization of Classical Physics that includes classical laws as special cases.

Quantum Physics extends that range to the region of small dimensions.

Just as ‘c’ the velocity of light signifies universal constant, the Planck's constant characterizes Quantum Physics.

$$h = 6.625 \times 10^{-27}\, erg.\mathrm{sec}$$

$$h = 6.625 \times 10^{-34}\, Joule.\mathrm{sec}$$

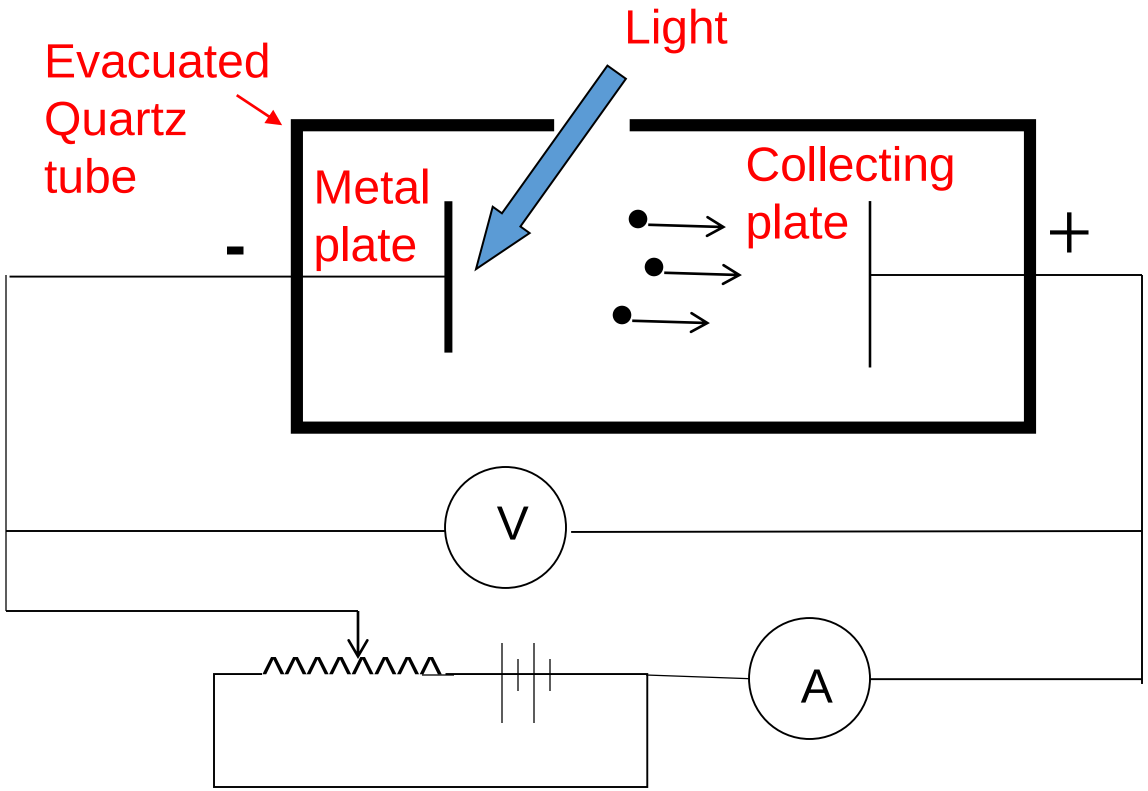
Quantum Mechanics is able to explain

1. Photo electric effect
2. Black body radiation
3. Compton effect
4. Emission of line spectra

The most outstanding development in modern science was the conception of Quantum Mechanics in 1925. This new approach was highly successful in explaining about the behavior of atoms, molecules and nuclei.

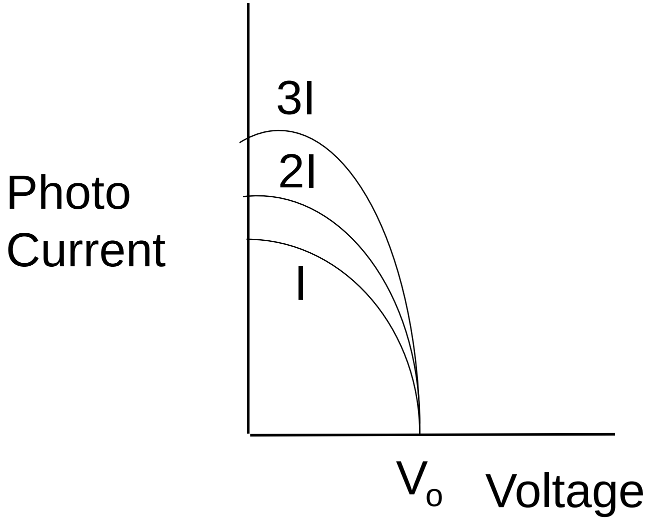
Photo Electric Effect

The **emission of electrons** from a metal plate when illuminated **by light or any other radiation of any wavelength or frequency <u>(suitable)</u>** is called **photoelectric effect**. The emitted electrons are called **'photo electrons'**.



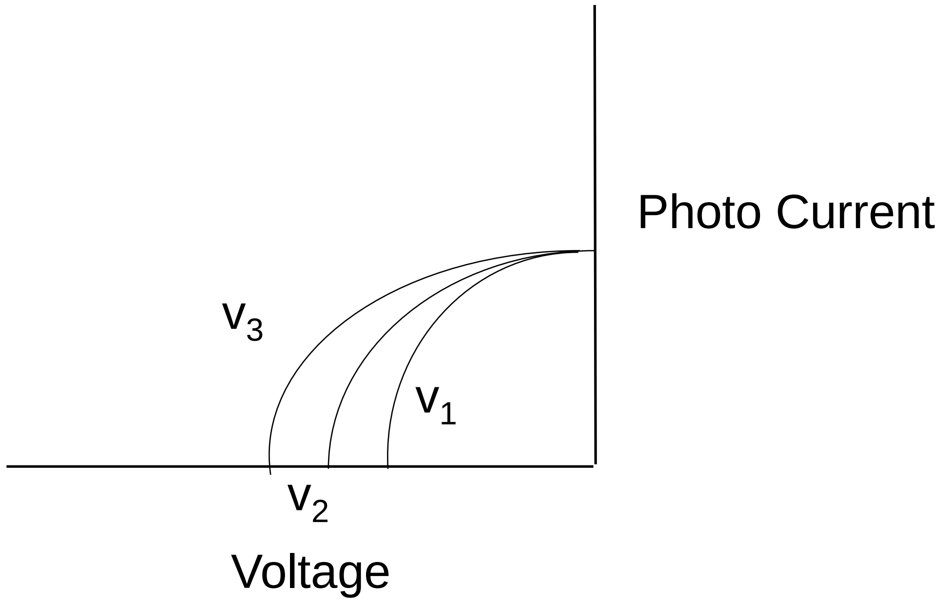
Experimental findings of the photoelectric effect

1. There is **no time lag** between the **arrival of light at the metal surface and the emission of photoelectrons**.
2. When the **voltage is increased** to a certain value say V_o, the photocurrent reduces to zero.
3. **Increase in intensity** increase the number of the photoelectrons but the electron energy remains the same.



Experimental findings of the photoelectric effect

4. Increase in **frequency of light increases the energy** of the electrons. At frequencies below a certain critical frequency (characteristics of each particular metal), no electron is emitted.



5. There exists a **characteristic frequency for each metal** to observe photoelectric effect, below which there is no emission of electrons called **threshold frequency**.

Einstein's Photo Electric Explanation

The energy of a incident photon is utilized in two ways

1. A part of energy is used to free the electron from the atom known as photoelectric work-function (W_o).
2. Other part is used in providing kinetic energy to the emitted electron . $\left(\frac{1}{2}mv^2\right)$

$$h\nu = W_o + \frac{1}{2}mv^2$$

This is called Einstein's photoelectric equation.

$$h\nu = W_o + KE_{\max}$$

$$h\nu = h\nu_o + KE_{\max}$$

$$KE_{\max} = h(\nu - \nu_o)$$

If $\nu < \nu_o$, no photoelectric effect

$$W_o = h\nu_o = \frac{hc}{\lambda_o}$$

$$\lambda_o = \frac{hc}{W_o} = \frac{12400}{W_o(eV)}\ \overset{o}{A}$$

If V_o is the stopping potential, then

$$KE_{\max} = h(\nu - \nu_o)$$

$$eV_o = h\nu - h\nu_o$$

$$V_o = \frac{h\nu}{e} - \frac{h\nu_o}{e}$$

It is in form of $y = mx + c$. The graph with V_o on y-axis and h/e on x-axis will be a straight line with slope ν

Photons

Einstein postulated the **existence of a particle** called a **photon**, to explain detailed results of photoelectric experiment.

$$E_p = h\nu = \frac{hc}{\lambda}$$

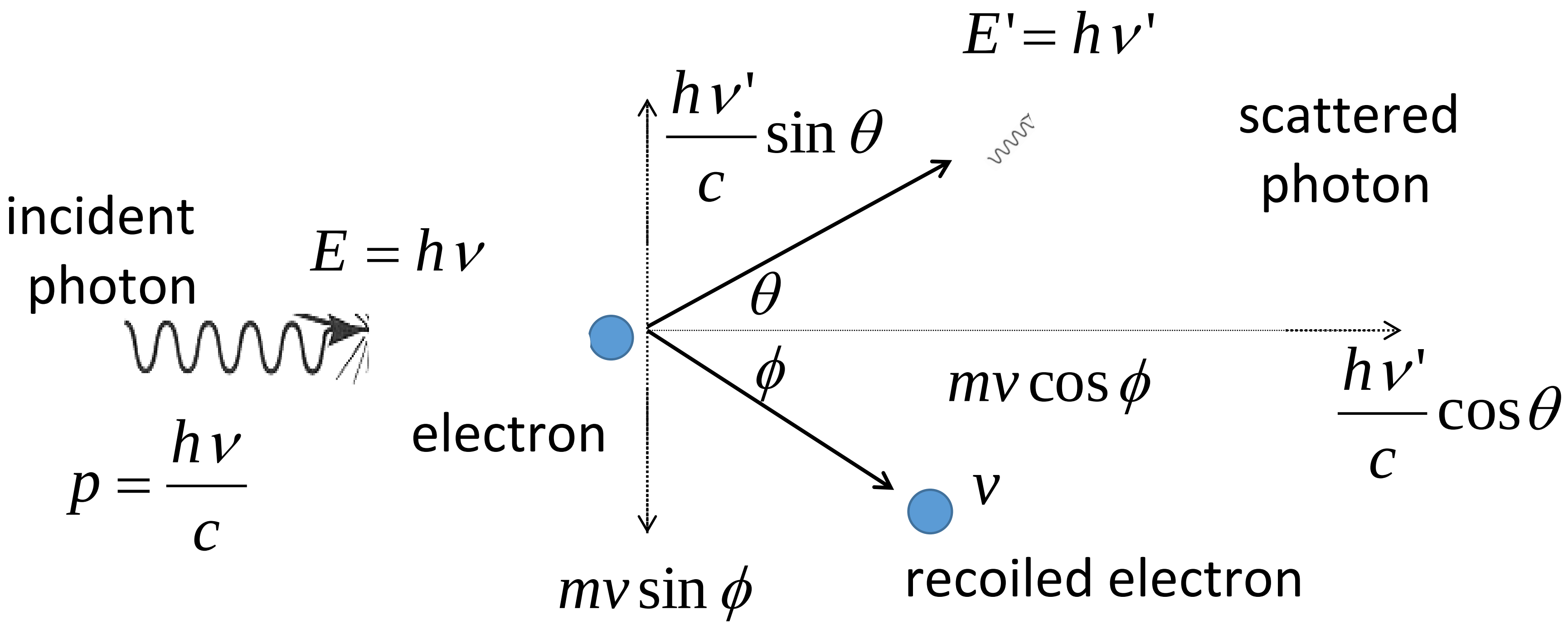
Photon has **zero rest mass**, travels at **speed of light**

Explains "instantaneous" emission of electrons in photoelectric effect, frequency dependence.

Compton Effect

When a ***monochromatic beam of X-rays*** is scattered from a material then both the wavelength of primary radiation (unmodified radiation) and the radiation of higher wavelength (modified radiation) are found to be present in the scattered radiation.

Presence of modified radiation in scattered X-rays is called ***Compton effect***.



From Theory of Relativity, total energy of the recoiled electron with v ~ c is

$$E = mc^2 = K + m_o c^2$$

$$K = mc^2 - m_o c^2$$

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

$$K = m_o c^2 \left[\frac{1}{\sqrt{1 - v^2/c^2}} - 1 \right]$$

Similarly, momentum of recoiled electron is

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

Now from Energy Conversation

$$h\nu = h\nu' + m_o c^2 \left[\frac{1}{\sqrt{1 - v^2/c^2}} - 1 \right] \qquad \text{(i)}$$

From Momentum Conversation

$$\frac{h\nu}{c} = \frac{h\nu'}{c}\cos\theta + \frac{m_o v}{\sqrt{1 - v^2/c^2}}\cos\phi \qquad \text{(ii)}$$

along x-axis

and

$$0 = \frac{h\nu'}{c}\sin\theta - \frac{m_o v}{\sqrt{1 - v^2/c^2}}\sin\phi \qquad \text{(iii)}$$

along y-axis

Rearranging (ii) and squaring both sides

$$\left(\frac{h\nu}{c}-\frac{h\nu'}{c}\cos\theta\right)^2=\frac{m_o^2v^2}{1-v^2/c^2}\cos^2\phi \qquad \text{(iv)}$$

Rearranging (iii) and squaring both sides

$$\left(\frac{h\nu'}{c}\sin\theta\right)^2=\frac{m_o^2v^2}{1-v^2/c^2}\sin^2\phi \qquad \text{(v)}$$

Adding (iv) and (v)

$$\left(\frac{h\nu}{c}\right)^2+\left(\frac{h\nu'}{c}\right)^2-\frac{2h^2\nu\nu'}{c^2}\cos\theta=\frac{m_o^2v^2}{1-v^2/c^2} \qquad \text{(vi)}$$

From equation (i)

$$\frac{h\nu}{c}-\frac{h\nu'}{c}+m_oc=\frac{m_oc}{\sqrt{1-v^2/c^2}}$$

On squaring, we get

$$\left(\frac{h\nu}{c}\right)^2+\left(\frac{h\nu'}{c}\right)^2+m_o^2c^2-\frac{2h^2\nu\nu'}{c^2}+2hm_o(\nu-\nu')=\frac{m_o^2c^2}{1-v^2/c^2}$$

(vii)

Subtracting (vi) from (vii)

$$-\frac{2h^2\nu\nu'}{c^2}(1-\cos\theta)+2hm_o(\nu-\nu')=0$$

$$2hm_o(\nu-\nu')=\frac{2h^2\nu\nu'}{c^2}(1-\cos\theta)$$

$$m_o(\nu-\nu')=\frac{h\nu\nu'}{c^2}(1-\cos\theta)$$

But $\nu = \frac{c}{\lambda}$ and $\nu' = \frac{c}{\lambda'}$ So,

$$m_o c\left(\frac{1}{\lambda} - \frac{1}{\lambda'}\right) = \frac{h}{\lambda\lambda'}(1-\cos\theta)$$

$$m_o c\left(\frac{\lambda' - \lambda}{\lambda\lambda'}\right) = \frac{h}{\lambda\lambda'}(1-\cos\theta)$$

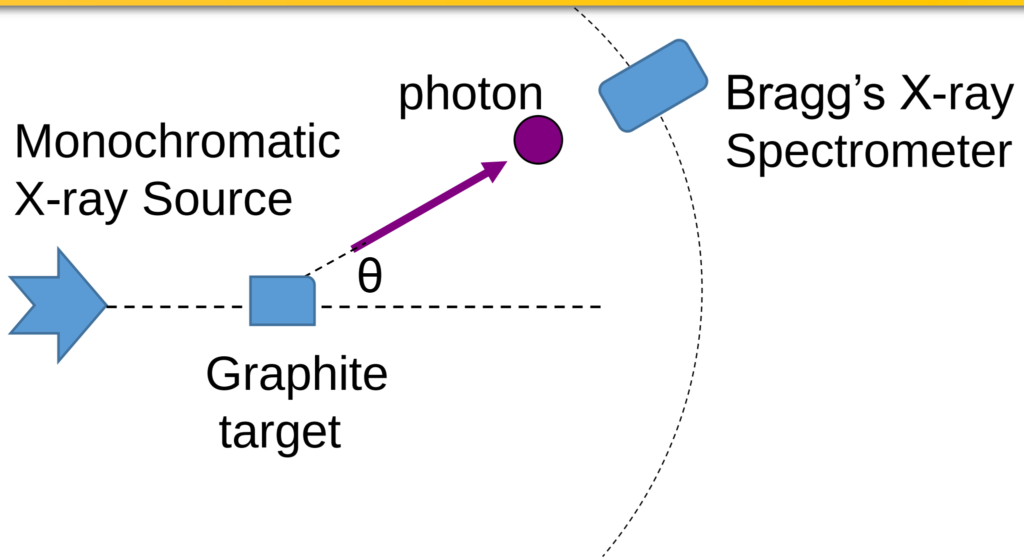
$$\lambda' - \lambda = \Delta\lambda = \frac{h}{m_o c}(1-\cos\theta)$$

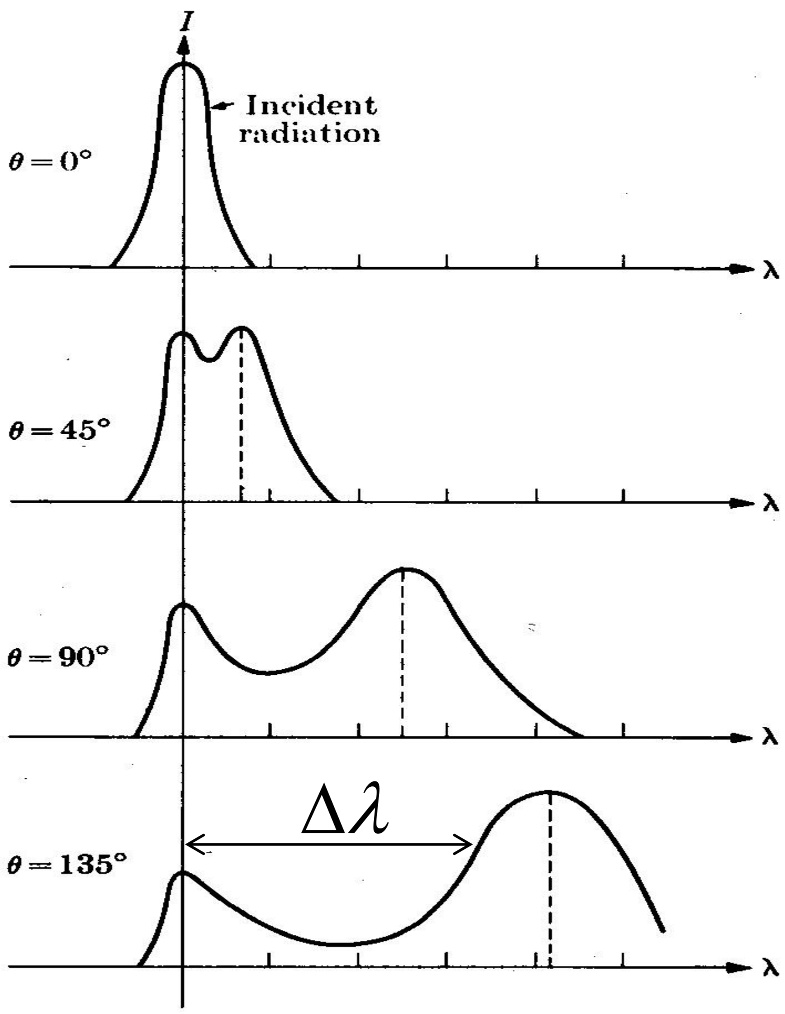
$\Delta\lambda$ is the Compton Shift.

It neither depends on the incident wavelength nor on the scattering material. It only on the scattering angle i.e. θ

$\frac{h}{m_o c}$ is called the Compton wavelength of the electron and its value is 0.0243 Å.

Experimental Verification





1. One peak is found at same position. This is unmodified radiation

2. Other peak is found at higher wavelength. This is modified signal of low energy.

3. $\Delta\lambda$ increases with increase in θ.

Compton effect can't observed in Visible Light

$$\Delta\lambda = \frac{h}{m_o c}(1-\cos\theta) = 0.0243\ (1-\cos\theta)\ \text{Å}$$

$\Delta\lambda$ is maximum when (1- cosθ) is maximum i.e. 2.

$$\Delta\lambda_{\max} = 0.05\ \text{Å}$$

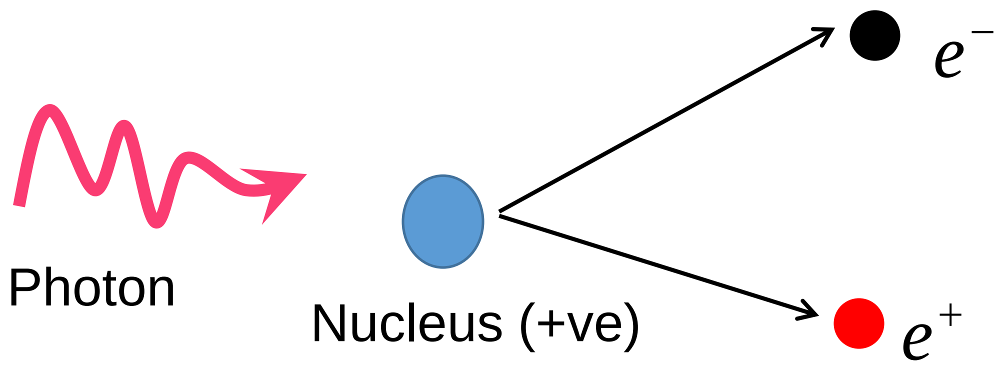
So Compton effect can be observed only for radiation having wavelength of few Å.

For $\lambda = 1$Å $\Delta\lambda$ ~ 1%

For $\lambda = 5000$Å $\Delta\lambda$ ~ 0.001% (undetectable)

Pair Production

When a photon (electromagnetic energy) of sufficient energy passes near the field of nucleus, it materializes into an electron and positron. This phenomenon is known as pair production.



In this process charge, energy and momentum remains conserved prior and after the production of pair.

The rest mass energy of an electron or positron is 0.51 MeV (according to $E = mc^2$).

The minimum energy required for pair production is 1.02 MeV.

Any additional photon energy becomes the kinetic energy of the electron and positron.

The corresponding maximum photon wavelength is 1.2 pm. Electromagnetic waves with such wavelengths are called gamma rays . (γ)

Pair Annihilation

When an electron and positron interact with each other due to their opposite charge, both the particle can annihilate converting their mass into electromagnetic energy in the form of two γ - rays photon.

$$e^- + e^+ \rightarrow \gamma + \gamma$$

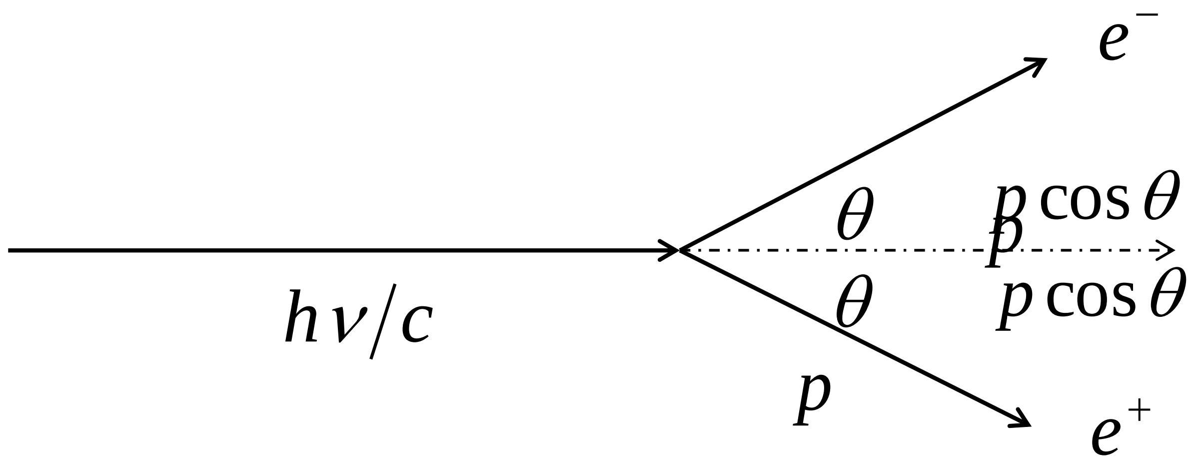
Charge, energy and momentum are again conversed. Two γ- photons are produced (each of energy 0.51 MeV plus half the K.E. of the particles) to conserve the momentum.

Pair production cannot occur in empty space

From conservation of energy

$$h\nu = 2m_o c^2 \gamma$$

here m_o is the rest mass and $\gamma = 1\big/\sqrt{1 - v^2/c^2}$



In the direction of motion of the photon, the momentum is conserved if

$$\frac{h\nu}{c} = 2p\cos\theta$$

$$h\nu = 2cp\cos\theta \qquad \text{(i)}$$

Momentum of electron and positron is

$$p = m_o v\gamma$$

Equation (i) now becomes

$$h\nu = 2m_o cv\gamma\cos\theta$$

$$h\nu = 2m_o c^2\gamma\left(\frac{v}{c}\right)\cos\theta$$

But $\quad {}^{v}\!/_{c} < 1 \quad$ and $\quad \cos\theta \le 1$

$$h\nu < 2m_o c^2\gamma$$

But conservation of energy requires that

$$h\nu = 2m_o c^2 \gamma$$

Hence it is impossible for pair production to conserve both the energy and momentum unless some other object is involved in the process to carry away part of the initial photon momentum. Therefore pair production cannot occur in empty space.

Wave Particle Duality

Light can exhibit both kind of nature of waves and particles so the light shows wave-particle dual nature.

In some cases like interference, diffraction and polarization it behaves as wave while in other cases like photoelectric and compton effect it behaves as particles (photon).

De Broglie Waves

Not only the light but every materialistic particle such as electron, proton or even the heavier object exhibits wave-particle dual nature.

De-Broglie proposed that a moving particle, whatever its nature, has waves associated with it. These waves are called "**matter waves**".

Energy of a photon is

$$E = h\nu$$

For a particle, say photon of mass, m

$$E = mc^2$$

$$mc^2 = h\nu$$

$$mc^2 = \frac{hc}{\lambda}$$

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

Suppose a particle of mass, m is moving with velocity, v then the wavelength associated with it can be given by

$$\lambda = \frac{h}{mv} \quad \text{or} \quad \lambda = \frac{h}{p}$$

(i) If $v = 0 \Rightarrow \lambda = \infty$ means that waves are associated with **moving** material particles only.

(ii) De-Broglie wave does not depend on whether the moving particle is charged or uncharged. It means matter waves are not electromagnetic in nature.