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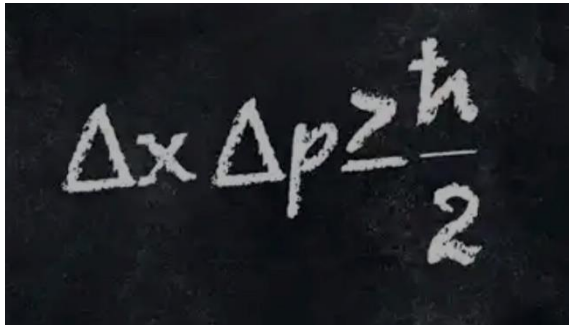
PHY 110 Engineering Physics

Lecture 1

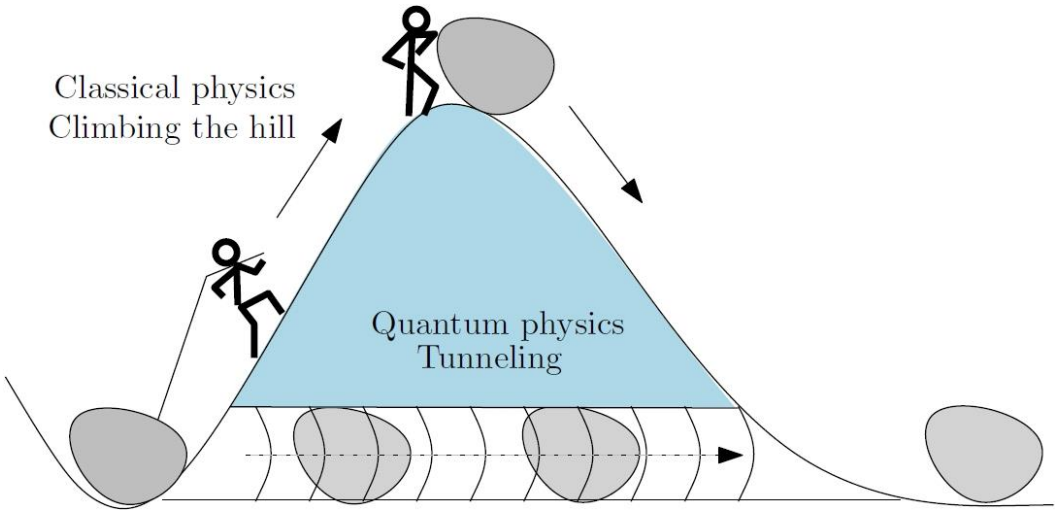
UNIT 4 –

Unit 4: Quantum mechanics

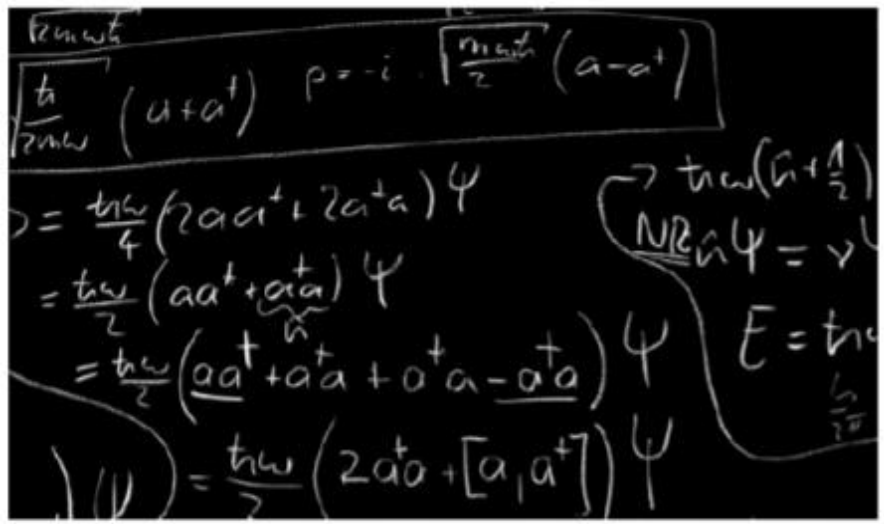


Need of quantum mechanics, photoelectric effect, concept of de Broglie matter waves, wavelength of matter waves in different forms, Heisenberg uncertainty principle, concept of phase velocity and group velocity (qualitative), wave function and its significance, Schrodinger time dependent and independent equation, particle in a box, tunneling effect (Qualitative idea).

$$\left[\frac{-\hbar^2}{2m}\nabla^2 + V(\mathbf{r})\right]\Psi(\mathbf{r}) = E\Psi(\mathbf{r})$$



Classical mechanics explains the very large

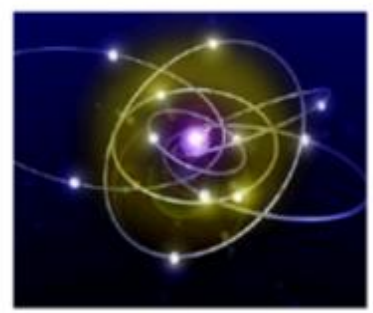


WHY DO WE NEED

QUANTUM MECHANICS?

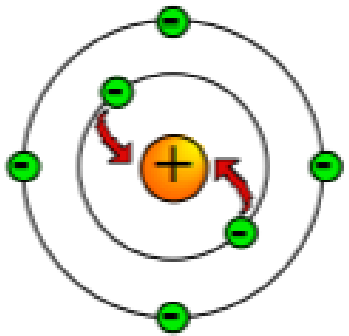
Quantum mechanics explains the very small

Classical mechanics is the study of the motion of everyday objects in accordance with the general principles first developed by Newton with later modifications by Einstein.



Quantum mechanics is a set of mathematical principles that attempts to explain the behavior of atoms and sub-atomic particles.

In the early 20th century experiments produced results that could not be explained by classical physics. For example, the solar system picture of an atom, first introduced by Ernest Rutherford in 1911 and modified by Neils Bohr in 1913



1. **Stability of atom** could not be explained by classical mechanics.. Because Motion of electron, protons etc could not be explained by Newton's law

Classical Physics was failure at atomic dimension! And Quantum Mechanics successfully explained the stability of atom☺

2) Spectral distribution of black body radiation

Planck's quantum hypothesis

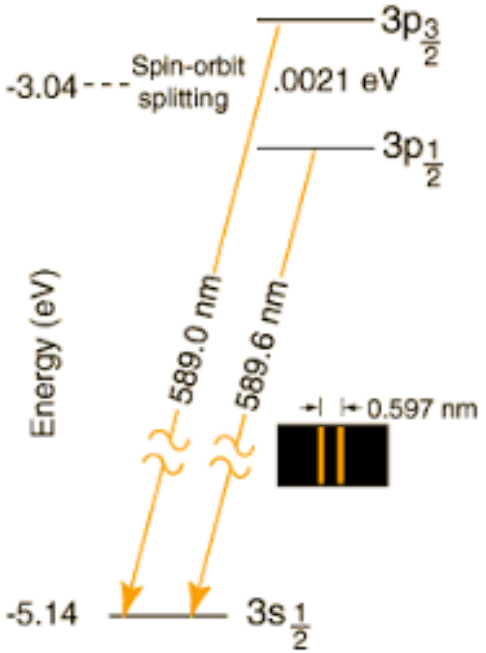
3) Origin of discrete spectra of atoms

4) Photoelectric effect

particle nature of light by Einstein

5) Compton effect

6) Raman effect



Classical mechanics failed to explain some phenomena and that was e
with Quantum mechanics !!

- Two unexplained events in the study of optics led to the creation of quantum theory.
- Why does molten metal emit light? (hotbody or blackbody radiation)
- Why does UV light discharge electrically charged metal plates? (photoelectric effect)

We will learn these two events today!

Down the memory lane

Quantum mechanics is one of the branches of physical sciences dealing with the behaviour of particle and wave on the scale of atoms or subatomic level.

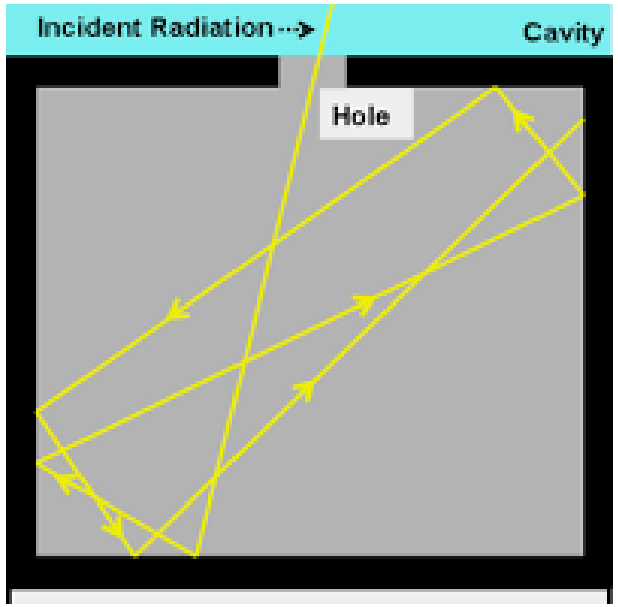
- 1900 It all started with Max Planck with the black-body problem..particle nature of wave
- 1905 Proof of the quantization of light by Einstein: Explained photo electric effect
- 1923 Louis de Broglie extends wave nature to particles

The **Planck, Einstein** and **de Broglie** relations illuminate the deep connections between energy with time, and space with momentum, and express wave–particle duality

- 1924 Quantum mechanics, the name first coined by Max Born
- 1926 Erwin Schrödinger developed wave equation
- 1927 Werner Heisenberg formulates the quantum uncertainty principle

Intense research between 1900 - 1928 led to the developments of quantum mechanics and we are going to study that in UNIT 4☺

BLACK BODY RADIATION

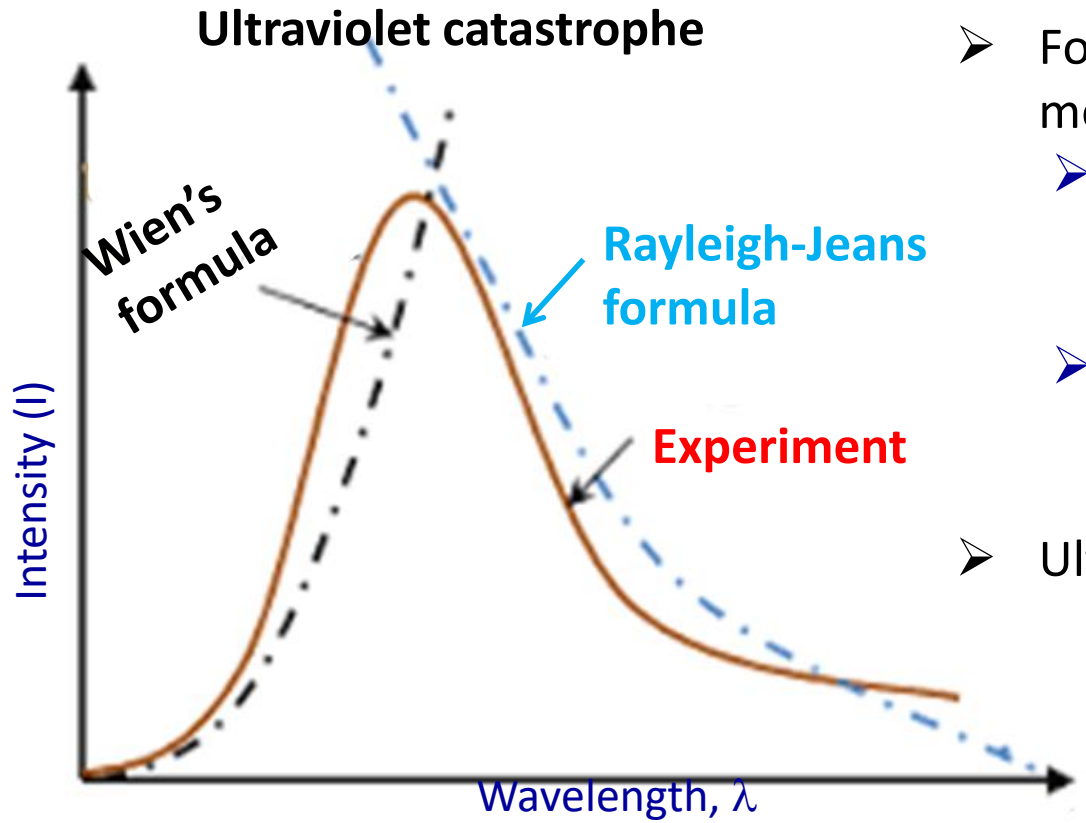


Close approximation of a black body

How do we see color?
What about the perception of color 'black' ??

When we heat this black body it radiate EM radiation of all frequencies

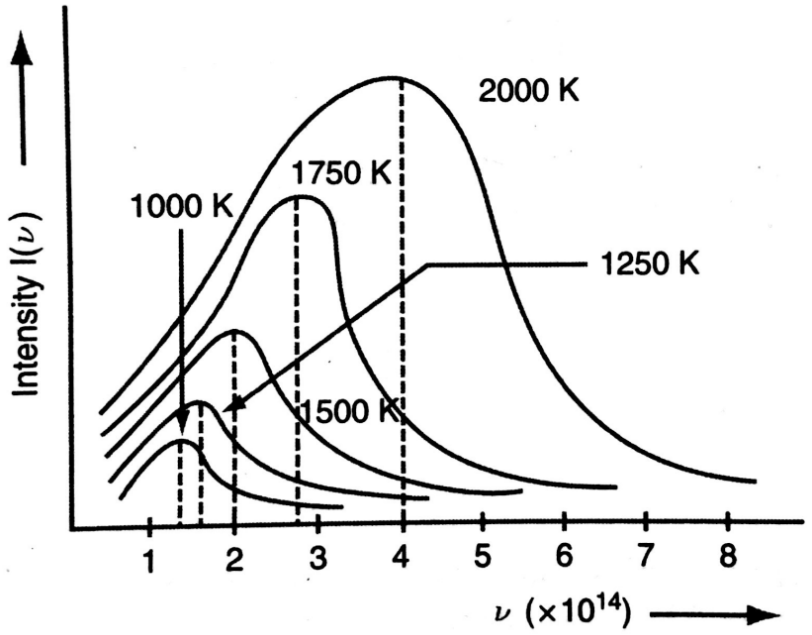
BLACK BODY RADIATION and Max Planck solution



- Formula derived using the classical mechanics partially explained
  - Low wavelength or higher frequencies wein's formula applied but valid at low T
  - Higher wavelength or lower frequencies Rayleigh-Jeans formula applied but valid at high T
- Ultraviolet catastrophe observed..

At this stage Max Planck stepped in and solved the problem
But how?... That paved the way for quantum mechanics!

BLACK BODY RADIATION and Max Planck solution

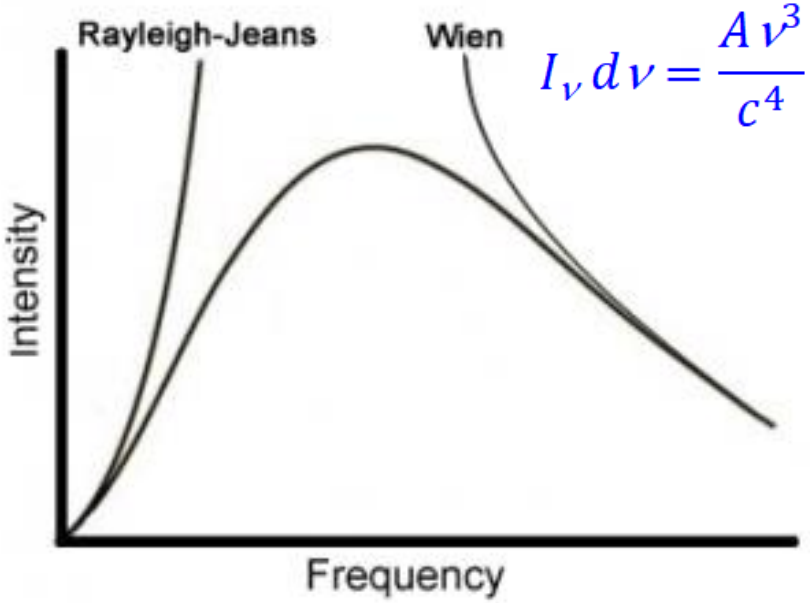


Intensity vs. Frequency

1) Distribution of frequencies depends on the Temperature of the black body
2) Intensity of radiation also depends on the temperature
3) All curve a goes through a peak, and peak position shift towards higher frequencies as the temperature increases.

BLACK BODY RADIATION and Max Planck solution

$$I_\nu d\nu = \frac{8\pi \nu^2}{c^3} kT \, d\nu$$



$$I_\nu d\nu = \frac{A\nu^3}{c^4} e^{-B\nu/T} \, d\nu$$

Explanations based on classical physics

- Standing waves and modes→ Rayleigh –Jean law
- Intensity of radiation reached a maximum at particular frequency or wavelength →Wien law

BLACK BODY RADIATION and Max Planck solution

Max Planck in 1900 assumed atomic oscillator responsible for EM radiation from black body.. But he again imposed few restrictions on it as follows, collectively known as Planck's hypothesis for black body radiation.

1. An oscillator can not have any arbitrary value of energy but can have only discrete energies as per the following relation

$E = nh\nu$ Where n =0,1,2,3…. ν and h are the frequency of oscillation and Planck's constant.

2. This oscillator can emit or absorb energy only in the form of packets of energy ($h\nu$) but no continuously.

$$\Delta E = \Delta n\, h\nu ; where\ \Delta E = E_2 - E_1\ and\ \Delta n = n_2 - n_1$$

BLACK BODY RADIATION and Max Planck solution

Planck's radiation formula

The energy density of radiation I_ν in the frequency range ν and $\nu+d\nu$ is given by

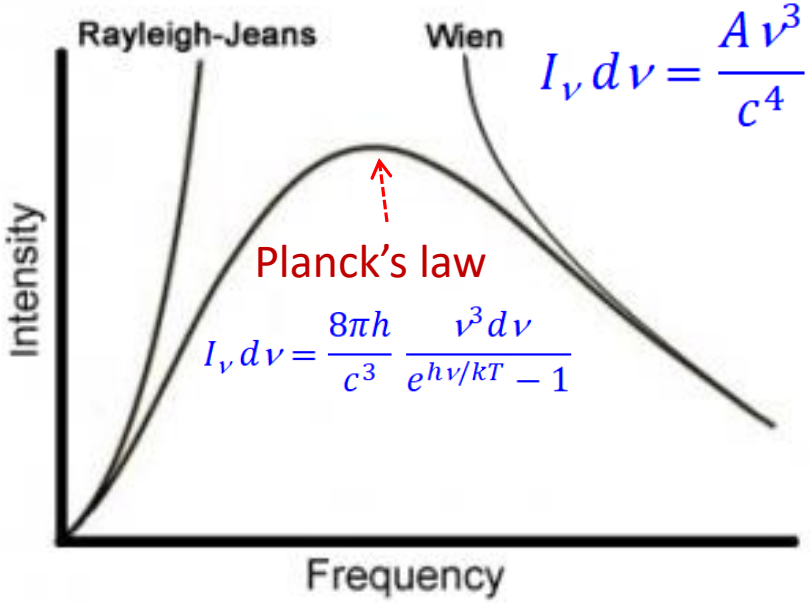
$$I_\nu d\nu = \frac{8\pi\nu^2}{c^3} d\nu(\bar{E})$$

But average energy of a Planck's oscillator is given by $\bar{E} = \frac{h\nu}{e^{h\nu/kT} - 1}$ and the above equation changes to

$$I_\nu d\nu = \frac{8\pi h}{c^3} \frac{\nu^3 d\nu}{e^{h\nu/kT} - 1}$$

This equation is known as Planck's radiation formula. Found some where a few weeks back.. Can you remember??

$$I_\nu d\nu = \frac{8\pi \nu^2}{c^3} kT \, d\nu$$



$$I_\nu d\nu = \frac{A\nu^3}{c^4} e^{-B\nu/T} \, d\nu$$

Planck's law

$$I_\nu d\nu = \frac{8\pi h}{c^3} \frac{\nu^3 d\nu}{e^{h\nu/kT} - 1}$$

Planck's law successfully explained black body radiation. Further, from this law Wien law and Rayleigh –Jeans law can be derived as special cases.

What does that mean?

A black body appears black because it

a)Does not reflect light

b)Does not transmit light

c)Does absorb light

d)All of the above

Ans: D

If we heat a black body, it does

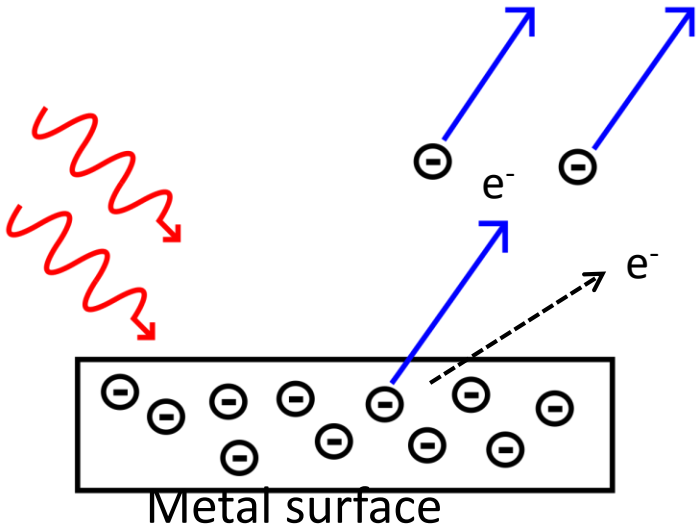
a) radiate electromagnetic radiation in the visible region only
b) radiate electromagnetic radiation in the infrared region only
c) radiate electromagnetic radiation in the ultra violet region only
d) radiate electromagnetic radiation in the entire EM spectrum

Ans: D

Photoelectric effect

The photoelectric effect was discovered in 1887 by the German physicist **Heinrich Rudolf Hertz**!!

Light waves

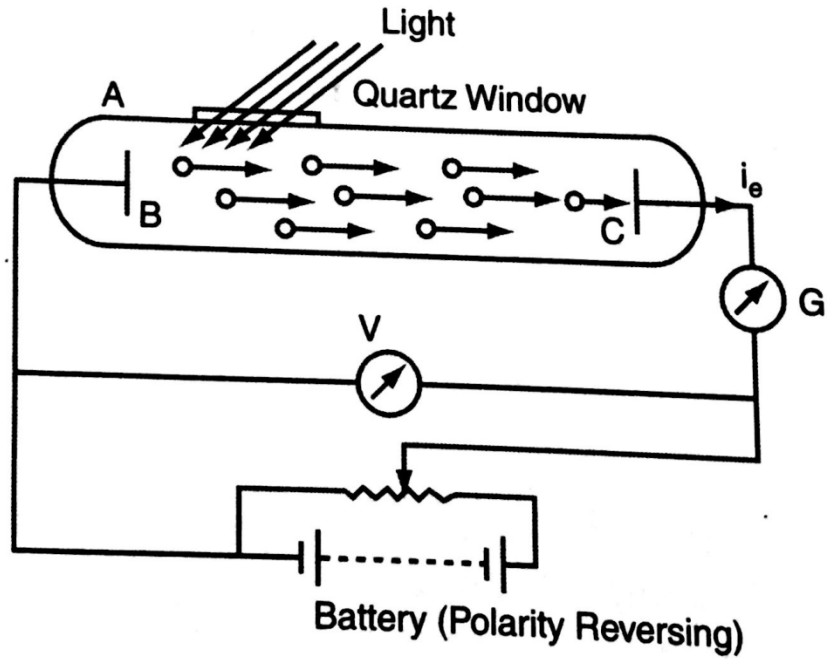


This effect says about the emission/ejection of electrons from the metal surface upon irradiation with light waves

Now we will see how this experiment is done and how to explain the result with classical mechanics

Photoelectric effect- Experiment

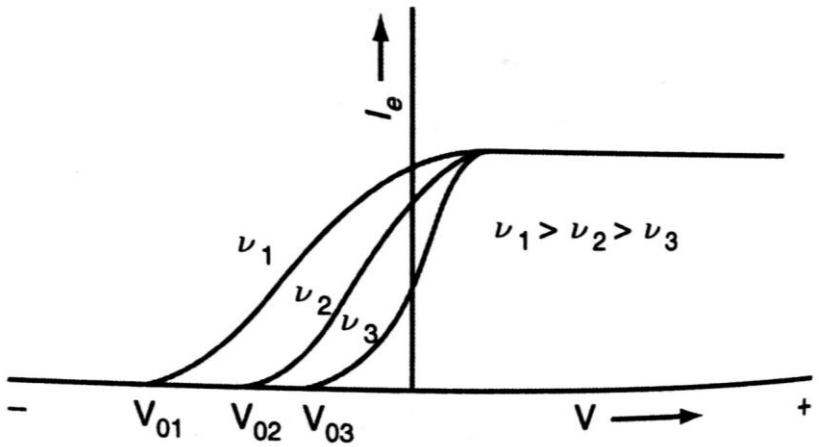
1) Vacuum tube (A) with a quartz window
2) Two metallic plates B and C
3) Voltage source
4) An ammeter
5) Voltmeter
6) Light



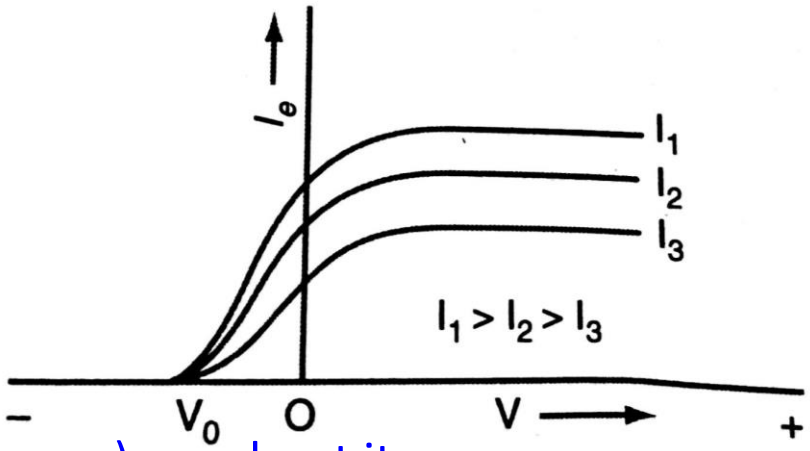
- Voltage is applied to plate B and C
- Light is allowed to fall on plate B
- Photo electrons produced at plate B move towards plate C where it get collected and current Ie flow through the circuit

PE effect- I-V characteristics

At various energies of light



At various intensities of light



What classical electro dynamics (Maxwell's EM theory) say about it…

- Electron with more energy will be ejected if irradiated with highly intense light (eg. LASER)
  - But more electrons with same energy came out (same V_o)
  - Energy increased only when the frequency of light increased (V_o changes)

Leonard found the saturated current (Is) does not have any influence on the energy of the ejected photoelectron, rather than it depended only on the intensity of the photon.

Photoelectric effect- Einstein's model

So electrons leave the surface with some kinetic energy, (E_k) if the photon energy is sufficiently high to knock out electron from the surface

$$E_k = h\nu - \phi_0$$

where, ϕ_0 is work function of the metal; energy required to remove electron from the surface to vacuum level

$$E_k = h\nu - h\nu_0$$ where $$h\nu_0 = \phi_0$$

So there is minimum light frequency called *threshold frequency* (ν_0) for given metal at which quantum of energy is equal to the work function

Light having energy below this will not cause photoemission

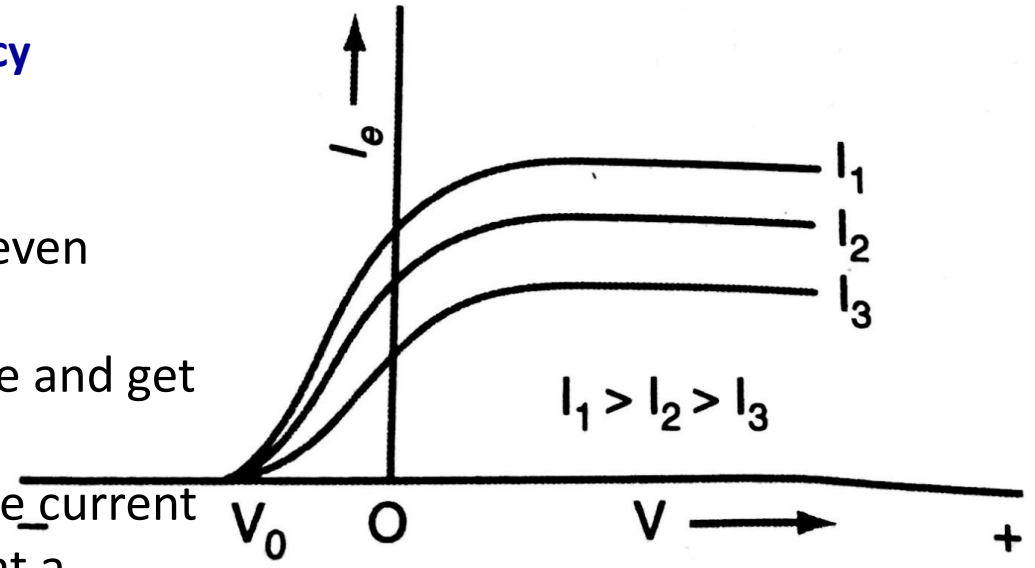
High intensity (number of photons/unit time) cause ejection of more electrons with the same kinetic energy

Excess energy is the kinetic energy of the photoelectron

PE effect- I-V characteristics

At various intensities of light (frequency constant)

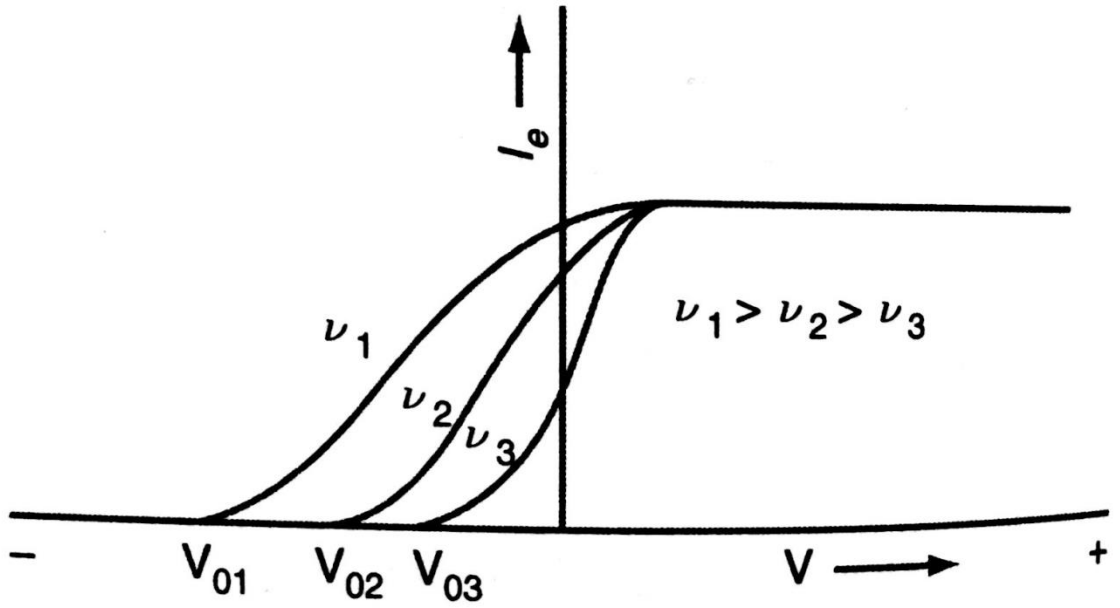
a) Current flow through the circuit even when there is no voltage
b) As the voltage increase it increase and get saturated
c) Reversing the polarity reduces the current and finally current become zero at a particular voltage **V_0** called the stopping potential



- Photoelectric current I_c increases with increasing intensity
- Current flows as soon as the plate is illuminated
- The maximum kinetic energy is independent of the intensity of radiation (same V_0 for different intensity)

Photoelectric effect- Einstein's model

At various energies of light
(Constant intensity)



- ✓ Maximum kinetic energy of the ejected electron depends on the energy of the incident radiation..
  - ✓Saturation current independent of the energy of incident radiation
  - ✓Higher energy higher is the stopping potential V_0

Photoelectric effect- Einstein's model

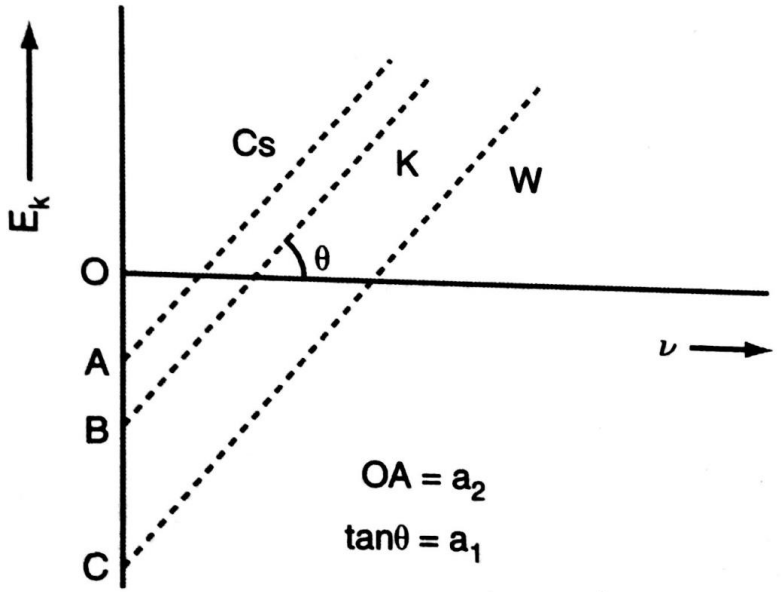
Have a look at PE equation of Einstein

$$E_k = h\nu - h\nu_0$$

And compare with the linear equation

$$y = mx + c$$

That means kinetic energy **E_k** linearly depended on the frequency **ν**



$$E_k = a_1\nu + a_2$$

a_1 is the slope and **a_2** is the Y-intercept.

a_2 different for different metals

a_1 remain same for all metal and is a constant

Seed for the development of QM

An outstanding achievement.. Constant is nothing but the Planck's constant..

Particle nature of light is thus undeniable and more over supported Max Planck's hypothesis.. And quantum mechanics started to evolve from these break through ideas.

So, to answer the original question,

Why do we need quantum mechanics?

I offer the following answers.

Newton's equations and Einstein's relativity explain the properties of macroscopic objects. But quantum mechanics is essential for understanding and quantifying ...

- the growth and properties of the universe after the Big Bang,
- the structure and properties of atoms,
- the microscopic and macroscopic properties of solids such as metals and semiconductors,
- the arrangement and properties of atoms at surfaces,
- the structure and stability of molecules,

Who gave the correct theoretical explanation for photoelectric effect by considering the particle nature of light?

a) Einstein
b) Planck
c) Hertz
d) Maxwell

Ans: A

Which of the following phenomena show the particle nature of light?

a) Photoelectric effect
b) Interference
c) Diffraction
d) Polarization

Ans: A