UNIT II - Quantum Mechanics

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Lecture for Engineering Physics students

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PLAN OF THE PRESENTATION

- Principles involved in Classical mechanics
- Inadequacies of Classical mechanics
- Overview of Quantum mechanics
- Principles involved and outcomes

Introduction

Classical Mechanics is based mainly on three Newton's laws

- Law of Inertia
- Law of Force
- Law of action and reaction

Concepts involved are

- Absolute time, mass and space
- Explains correct motion of macroscopic and microscopic bodies moving with non-relativistic speeds (v<<<<c)

Principles involved in classical mechanics

In **classical mechanics**

- Time and space are two independent entities
- No limit in particle velocity
- Since everything is deterministic, we can measure all quantities simultaneously
- The outcome of all measurements are repeatable and depends only on the accuracy of measuring device

Principles involved in classical mechanics

Light: Waves or particles

1678 : Huygens principle

Every point on primary wave front serves as a source of secondary wavelets such that the primary wave front at some time later time is the envelope of these wavelets

1704 : Newton's principle

Corpuscular theory: Due to the fact that light travels in straight line according to classical physics

Principles involved in classical mechanics

Light: Waves or particles

1801 : Thomas Young

Uses wave theory of light to produce constructive and destructive interference and explained Newton's rings

Thomas Young
1773-1829

Principles involved in classical mechanics

1816 : Polarization

Arago and Fresnel investigated the interference of polarized rays of light and found that two rays of polarized light at right angles to each other will never interfere.

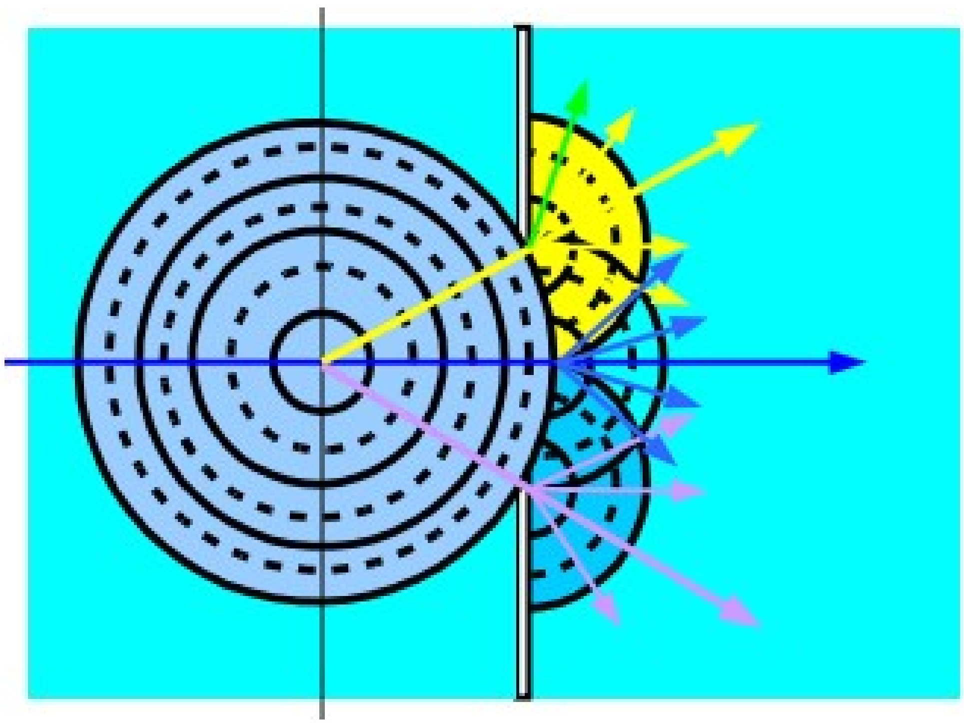
Dominique François Jean Arago 1786-1853

Augustin Jean Fresnel 1788-1827

Principles involved in classical mechanics

1818 : Diffraction

Fresnel by using Huygen's concept of secondary wavelets and explanation of interference, developed the theory of diffraction.



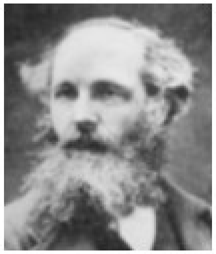
Augustin Jean Fresnel
1788-1827

Principles involved in classical mechanics

1865 : Electromagnetism

Maxwell's equations

James Clerk Maxwell
(1831-1879)



$\vec{H}$	***Magnetic Field Intensity***	$\left[A \cdot m^{-1}\right]$
$\vec{D}$	***Electric Displacement***	$\left[A \cdot s \cdot m^{-2}\right]$
$\vec{E}$	***Electric Field Intensity***	$\left[V \cdot m^{-1}\right]$
$\vec{B}$	***Magnetic Induction***	$\left[V \cdot s \cdot m^{-2}\right]$

Inadequacies of Classical Mechanics

Classical mechanics

- At the end of 19th century, Physics has evolved to the point at which Classical Mechanics was well established.

  - ✓ **Thermodynamics and kinetic theory was well established**
  - ✓ **Geometrical and physical optics was well established**
  - ✓ **Conservation laws for energy and momentum**

"There is nothing new to be discovered in Physics now. All that remains is more and more precise measurement" – Lord Kelvin

Inadequacies of Classical Mechanics

This is just before Relativity and Quantum mechanics appeared on the scene and opened up the ways for new exploration

Inadequacies of Classical Mechanics

- It does not holds good for atomic dimensions (non-relativistic speeds) i.e., electrons, protons, neutrons, etc.,
- Could not explain the stability of atoms
- Could not explain the observed spectrum of black body radiation
- Could not explain the variation of specific heat
- Could not explain the origin of discrete spectra
- Splitting of spectral lines

Origin of Quantum mechanics

- **Classical mechanics does not give any pointers to understand the quantum world.**

- **So, it became challenge for the young minds to understand exactly how the quantum world works…**

- **The features relating to quantum world were really obvious only through the atomic and sub microscopic phenomena.**

Origin of Quantum mechanics

- That is not to say that quantum mechanics does not hold good for macroscopic objects.

- In fact several macroscopic phenomena, I can think of ferromagnetism, paramagnetism in liquids right away…which can only be explained on the basis of quantum mechanics.

- Old quantum theory was proposed and developed by Neils Bohr, J.J.Thomson, etc.,

Origin of Quantum mechanics

- But Einstein found that no definitions, procedures and laws will work out when we deal with microscopic and sub-atomic particles.

- Thus, a new theory for dealing sub microscopic particles was developed and we call it now as Quantum Mechanics.

- Two master minds led this theory successful. They were the primary architects of quantum mechanics.

  - ✓ W.Heisenberg - matrix mechanics - Observables
  - ✓ E.Schroedinger - wave mechanics - Wavefunction & probability

Outcomes of Quantum mechanics

Dual nature of light and matter:

Wave nature of light……

- ✓ Interference
- ✓ Diffraction
- ✓ Polarization….

Particle / Corpuscular nature of light……

- ✓ Photoelectric effect
- ✓ Compton effect
- ✓ Discrete emission and absorption of radiation…
- ✓ **Light is propagated in small packets or bundles of energy $h\nu$ or $\hbar\omega$**
- ✓ **These packets are called photons (or) quanta and behave like corpuscles (particles)**

Outcomes of Quantum mechanics

De Broglie waves (or) Matter waves…………

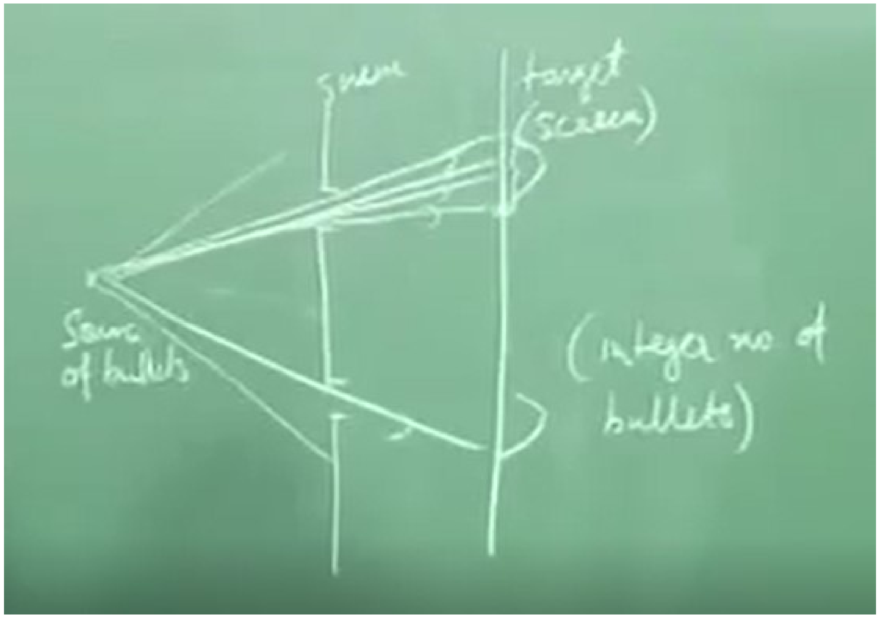
- ✓ In 1923-24, he proposed that idea of dual nature can be extended to all sub-atomic particles
- ✓ According to de Broglie a moving particle whatever its nature has a wave properties associated with it.
- ✓ The waves associated with material particles are called de Broglie waves (or) matter waves.

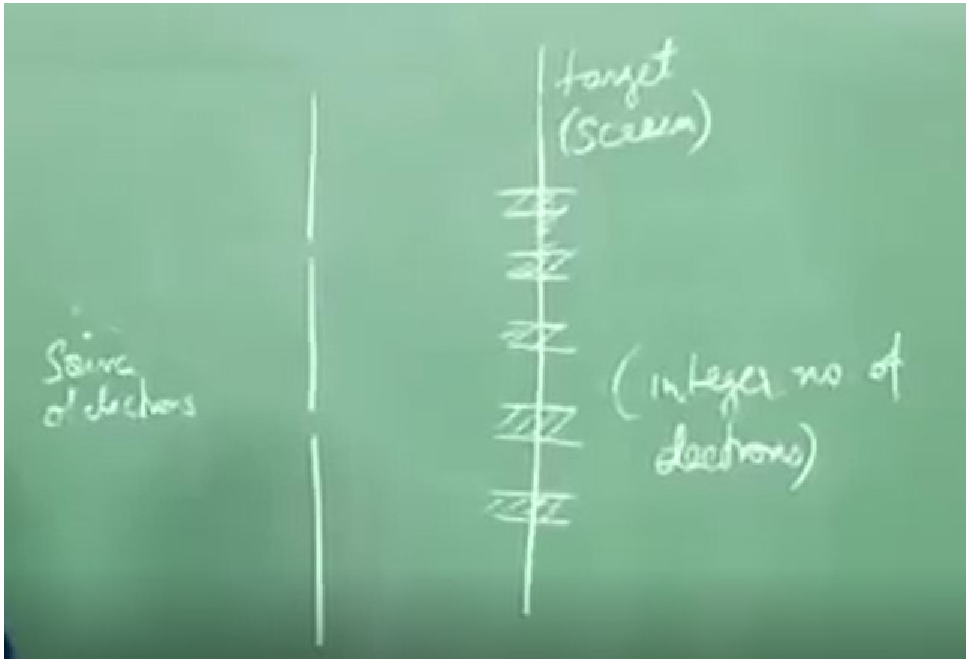
$$\lambda = h / p$$

$$\lambda = h / mv$$

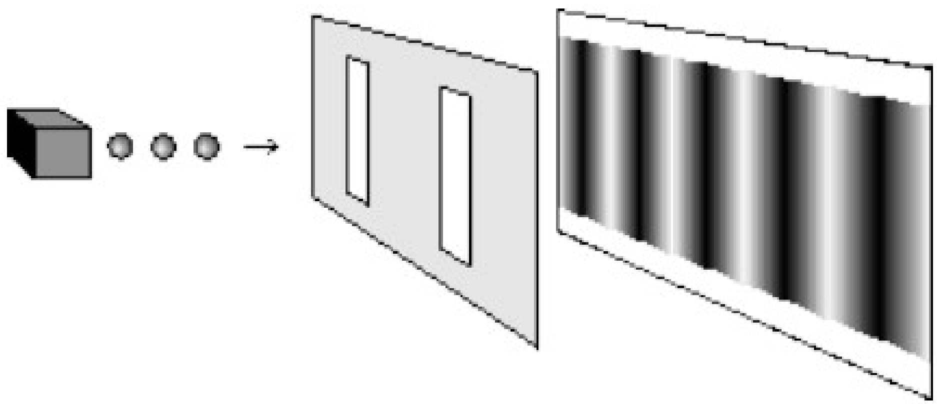
L. de BROGLIE

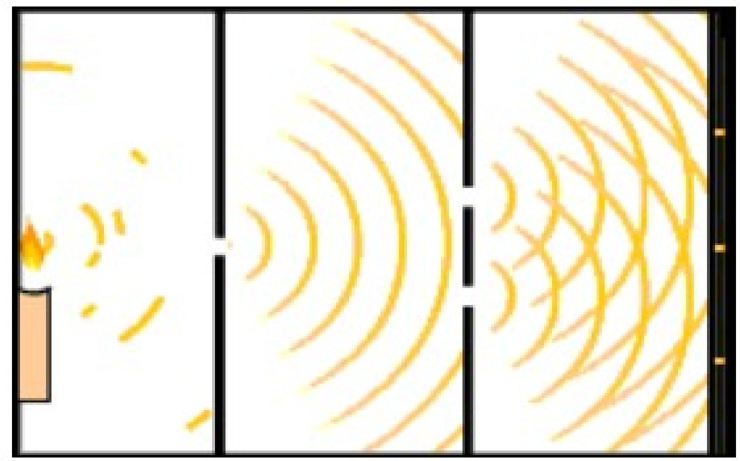
Young's double slit experiment

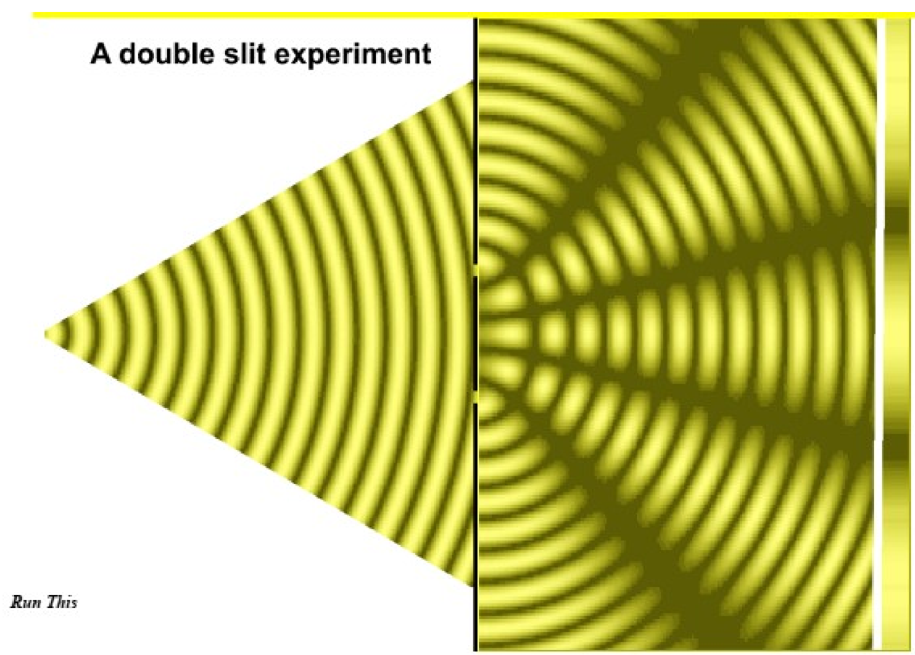


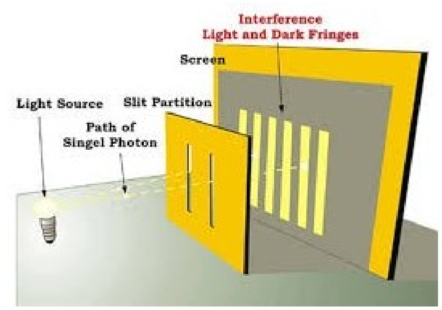


Young’s double slit experiment

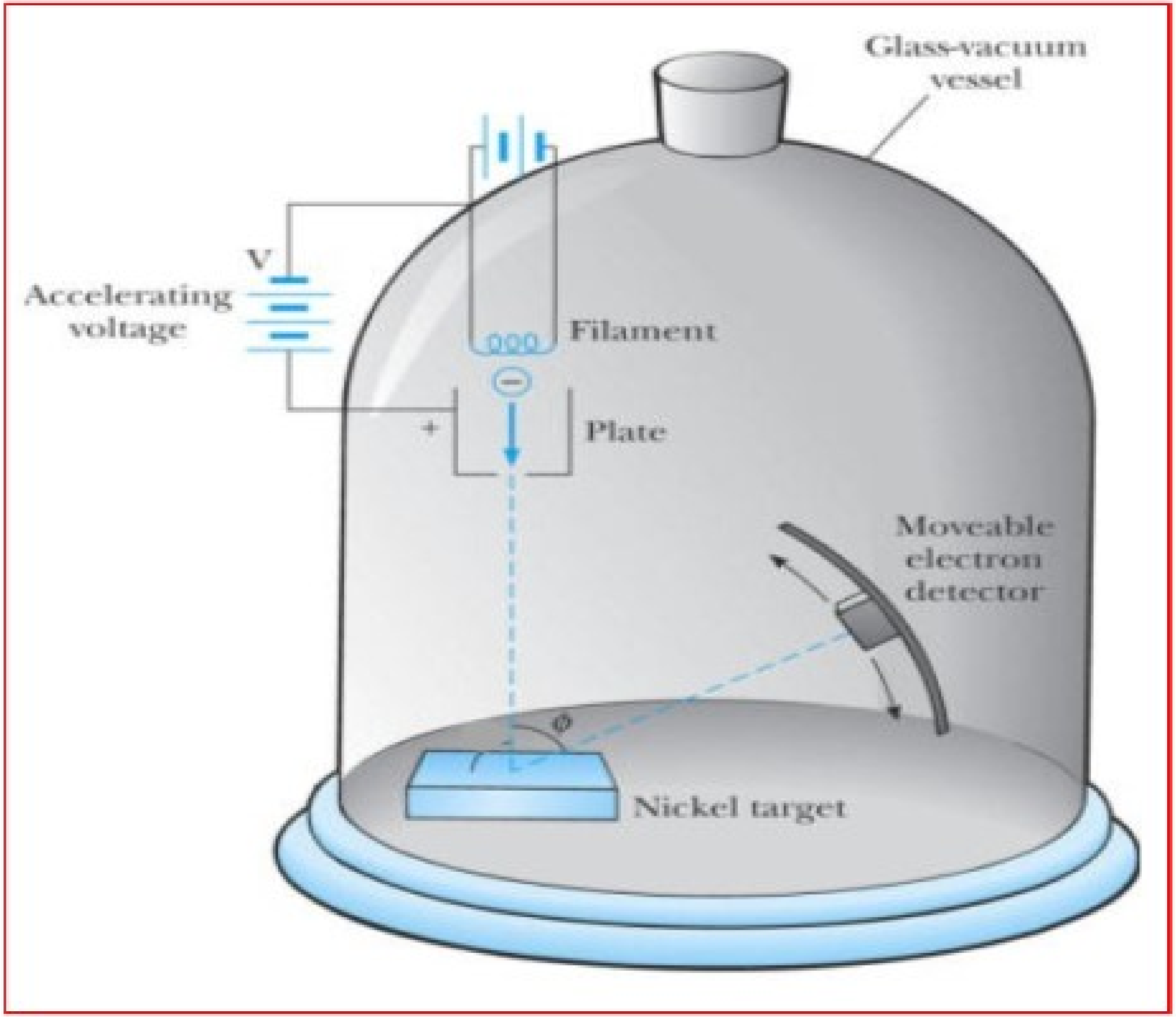








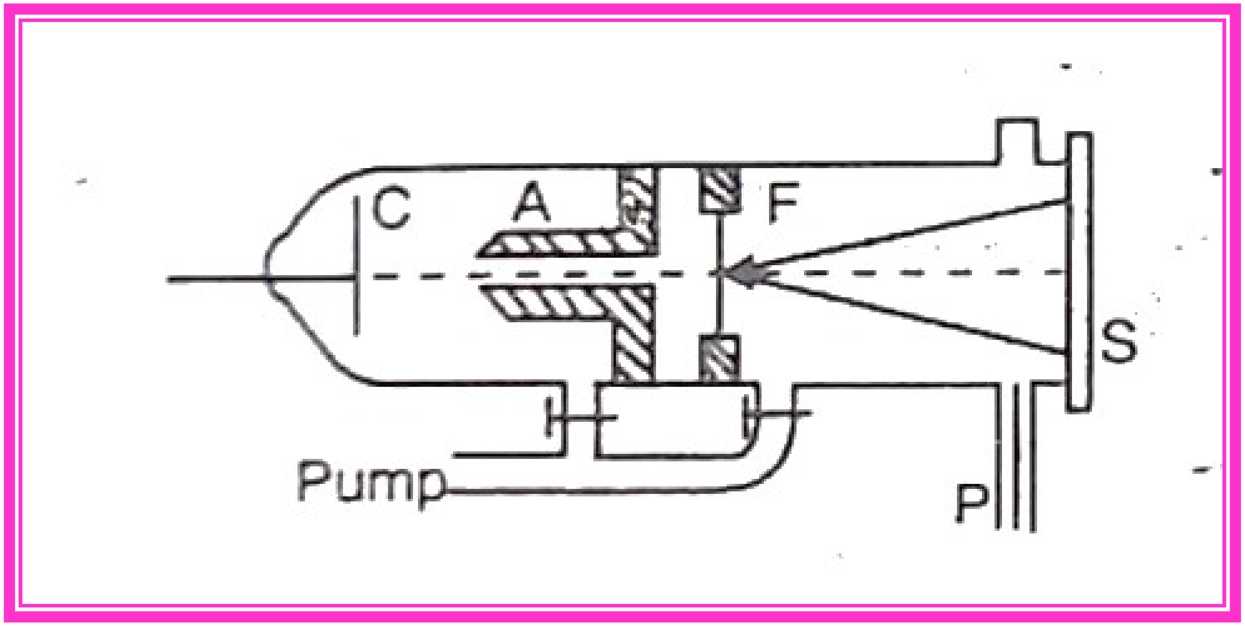
Davisson-Germer experiment



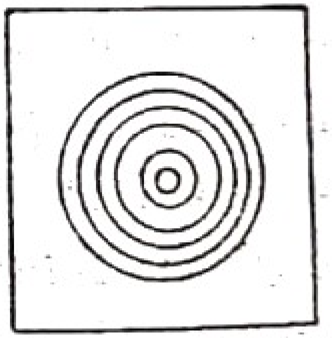
Lester Halbert Germer
1896 - 1971

Clinton Joseph Davisson
1881 – 1958
Nobel Prize 1937

G.P.Thomson experiment



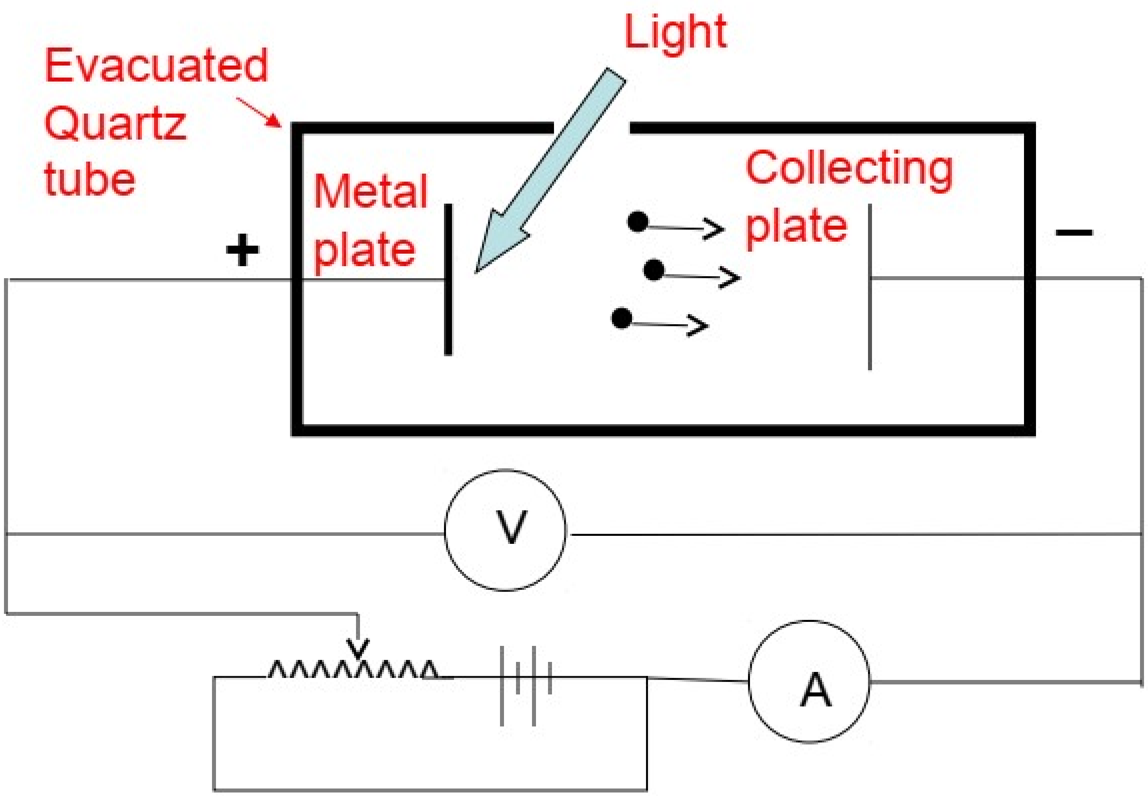
George Paget Thomson
1892 – 1975
Nobel Prize 1937



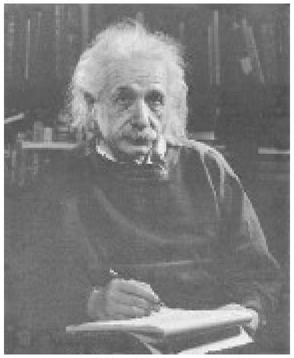
Using these results G.P. Thomson proved mathematically that the electron particles acted like waves, for which he received the Nobel Prize in 1937.

J.J. Thomson the father of G.P. proved that the electron is a particle in 1897, for which he received the Nobel Prize in 1906.

Photoelectric effect



Nobel Prize 1921



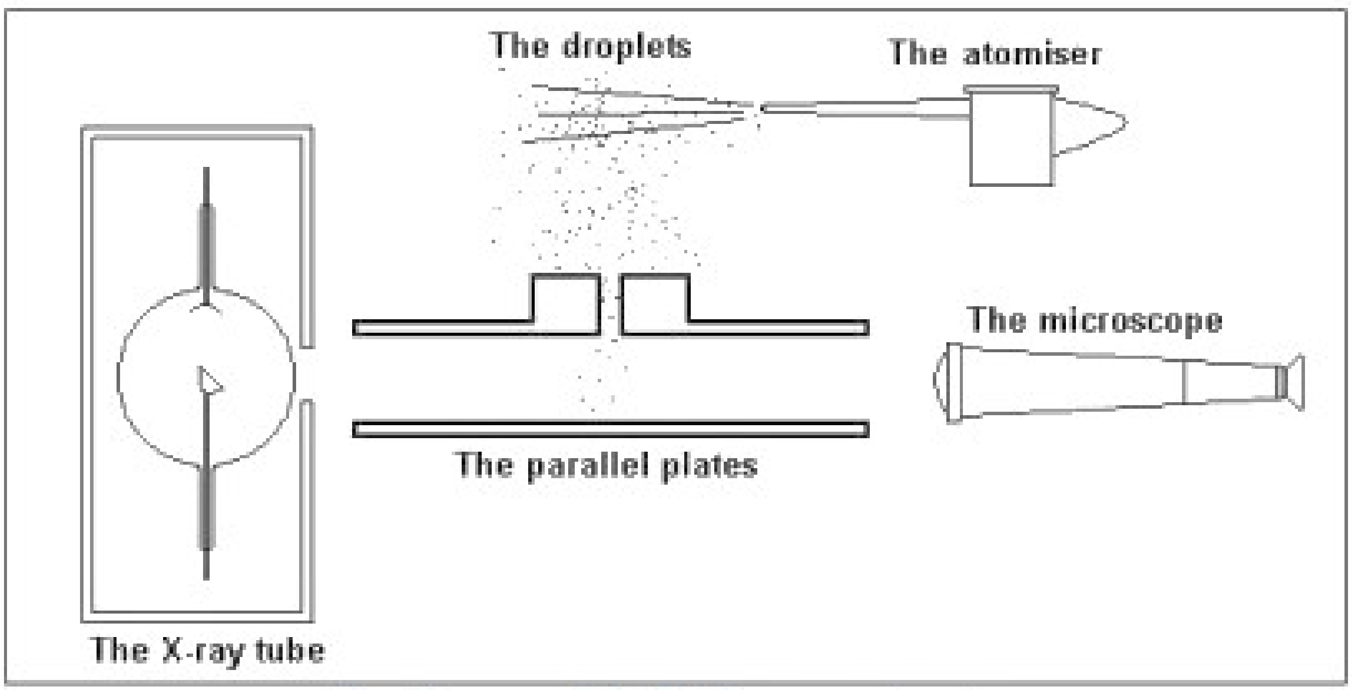
Albert Einstein
1879 - 1955

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

This is called Einstein's photoelectric equation.

Measurement of charge of electron

- Milliken's verification of Einstein's photoelectric equation **(Determination of h)**
- R.A.Millikan measured the charge of the electron by equalizing the weight mg of a charged oil drop with an electric field E.



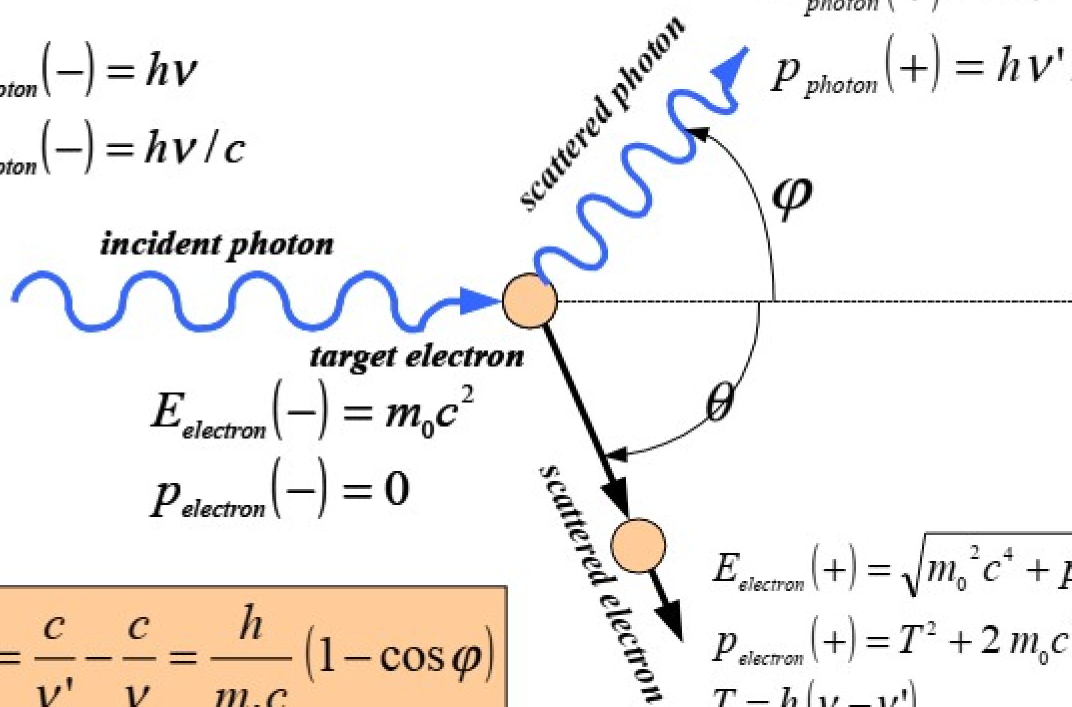
Robert Andrews Millikan
1868 – 1953
Nobel Prize 1923

Compton effect

❖ **Compton effect** – Electron photon scattering experiment

$$E_{photon}(-) = h\nu$$
$$p_{photon}(-) = h\nu / c$$

$$E_{photon}(+) = h\nu'$$
$$p_{photon}(+) = h\nu' / c$$

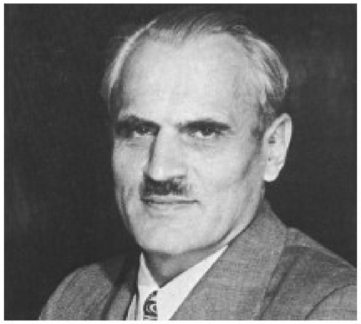


$$E_{electron}(-) = m_0 c^2$$
$$p_{electron}(-) = 0$$

$$E_{electron}(+) = \sqrt{m_0^2 c^4 + p_{photon}(-)^2 c^2}$$
$$p_{electron}(+) = T^2 + 2\, m_0 c^2 T$$
$$T = h(\nu - \nu')$$

$$\boxed{\lambda' - \lambda = \frac{c}{\nu'} - \frac{c}{\nu} = \frac{h}{m_0 c}(1 - \cos\varphi)}$$

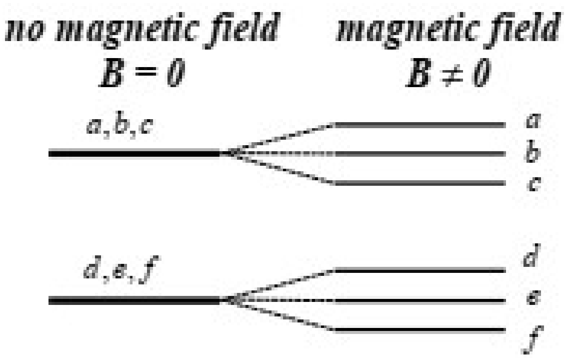
Nobel Prize 1927



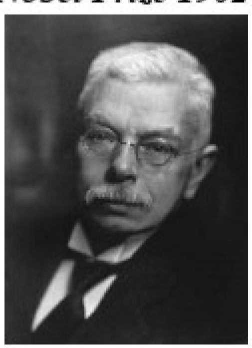
Arthur Holly Compton
1892 - 1962

Splitting of spectral lines - Zeeman effect

Pieter Zeeman observed that the spectral lines emitted by an atomic source splitted when the source is placed in a magnetic field



Nobel Prize 1902



Pieter Zeeman
1865 - 1943

http://en.wikipedia.org/wiki/Zeeman_effect

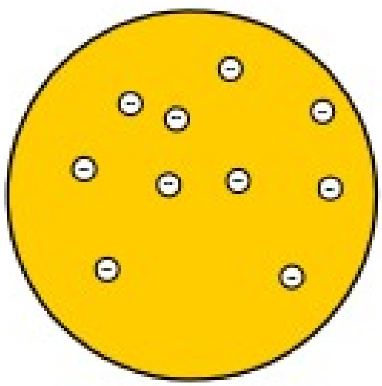
Atomic structure

- ✓ J.J.Thomson model
- ✓ Rutherford model
- ✓ Neil's Bohr model
- ✓ Willson Sommerfeld model &
- ✓ Vector atom model

J.J.Thomson model

Discovery of the electron:

J.J.Thomson showed in 1897 that the cathode rays are made of electrons and he measured the ratio of charge to mass ratio for the electron

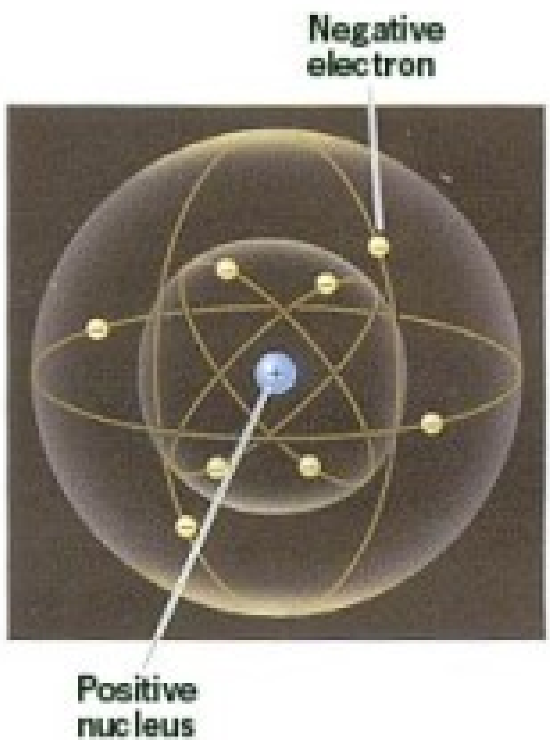


Plum Pudding Model

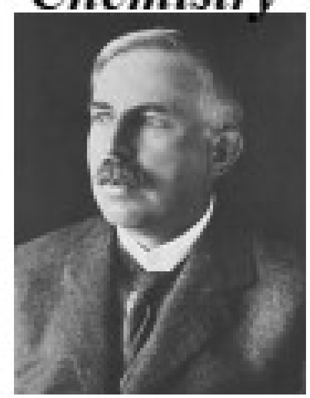
Joseph John Thomson
1856 – 1940
Nobel Prize 1922

Rutherford atom model

Ernest Rutherford finds the first evidence of protons. In 1908, he suggested that the positively charged atomic nucleus contains protons through his alpha particle scattering experiments.



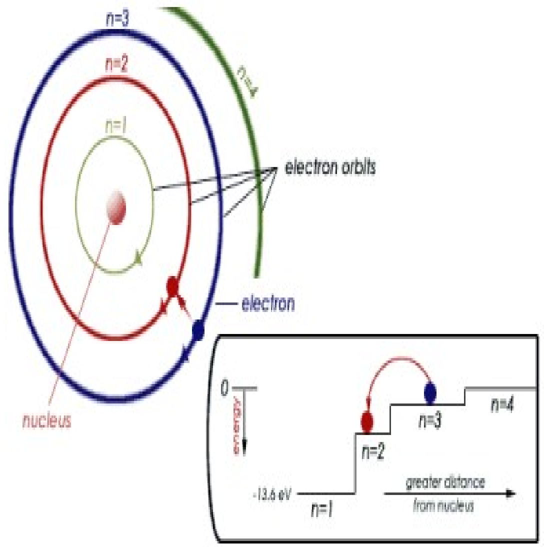
Nobel Prize 1908
Chemistry



Ernest Rutherford
1871 - 1937

Bohr atom model

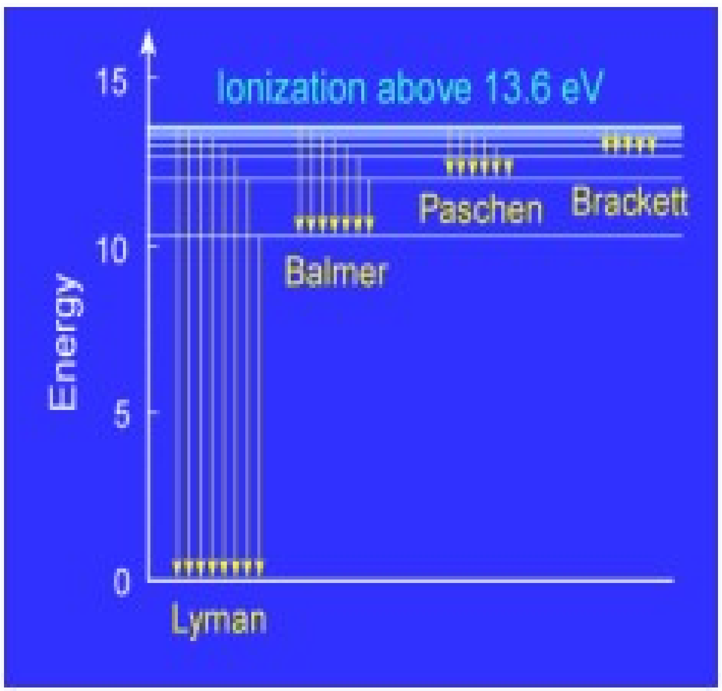
Neil’s Bohr presented his quantum model of an atom in 1913.

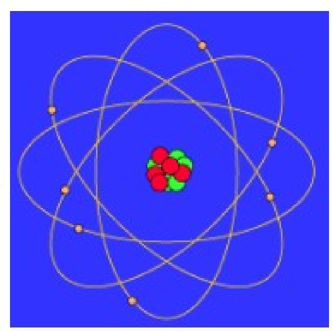


Nobel Prize 1922

Niels Bohr

1885 - 1962





Quantum exclusion principle

Wolfgang Pauli states the exclusion principle

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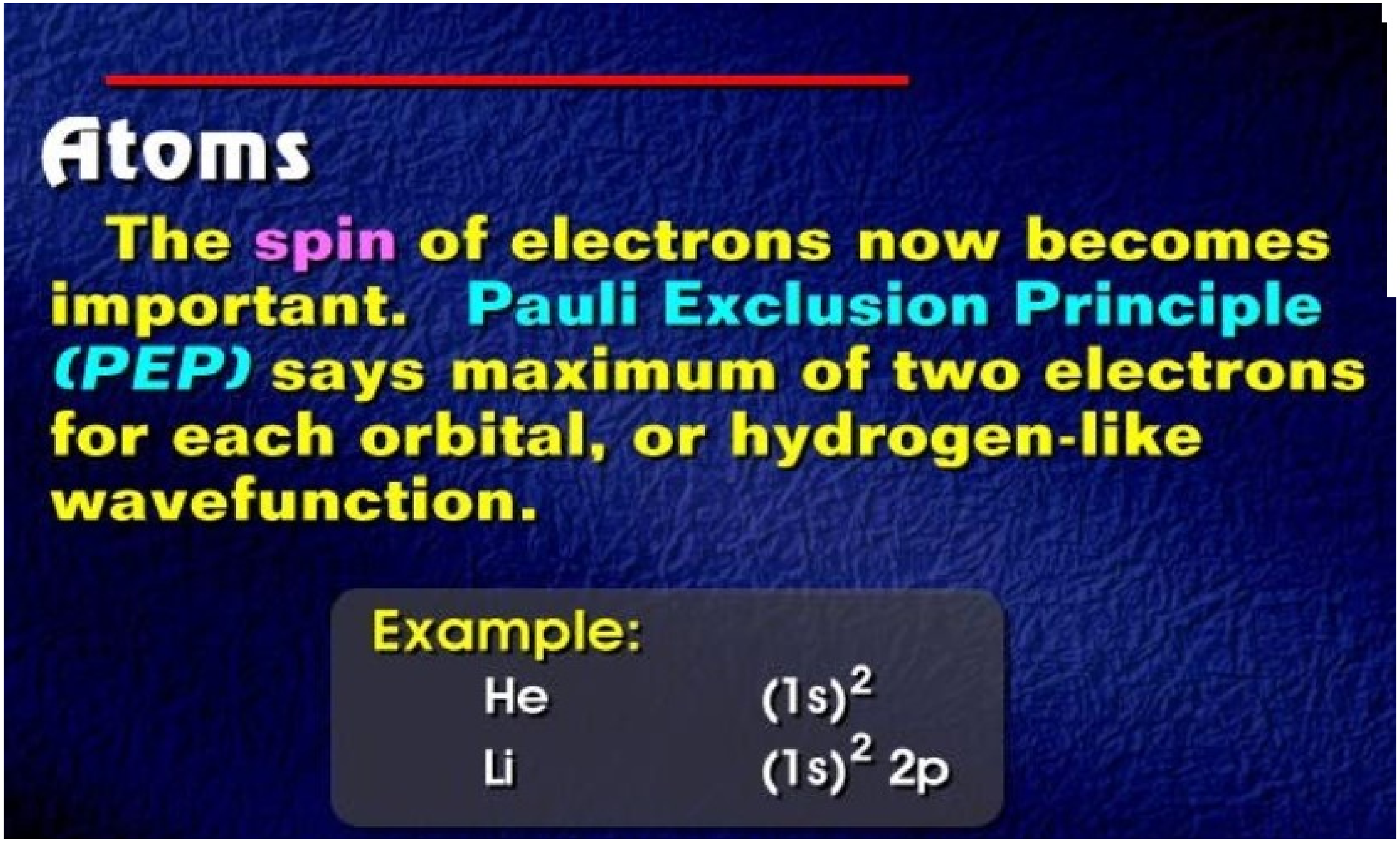
Nobel Prize 1945

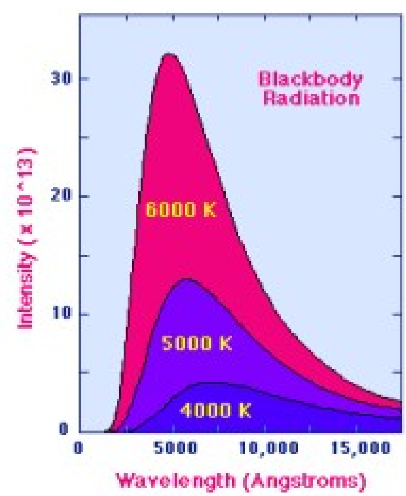
Wolfgang Pauli
1900 - 1958



Radiation principles involved in Quantum mechanics

- **Lummer and Pringsheim:** Distribution of energy among the radiation emitted by black body at different temperature.
- **Rayleigh-Jeans law:** Expression for the radiation energy per unit volume of a hot body.
- **Planck's radiation law:** Explained the experimentally observed distribution of energy in the spectrum of black body radiation.

$$E_\lambda = 8\pi hc / \lambda^5 [\exp(h\nu/kT) - 1]$$



Radiation principles involved in Quantum mechanics

- ❖ Wien's law matches well with Planck's law but Rayleigh-Jean's law does not holds good with Planck's law.

WILHELM WIEN (1864 - 1928)

Planck's law

Shorter λ

Longer λ

John William Strutt, 3rd Baron Rayleigh 1842- 1919

James Hopwood Jeans 1877 - 1946

Wien's law

MAX PLANCK (1858 - 1947)

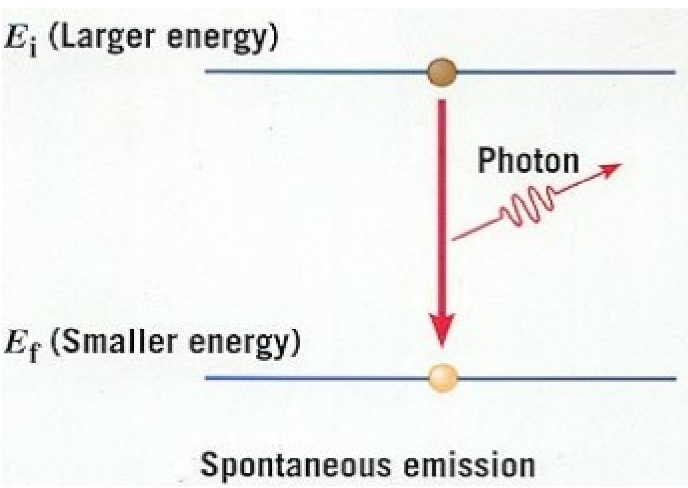
Rayleigh-Jean's law

Outcomes of Quantum mechanics

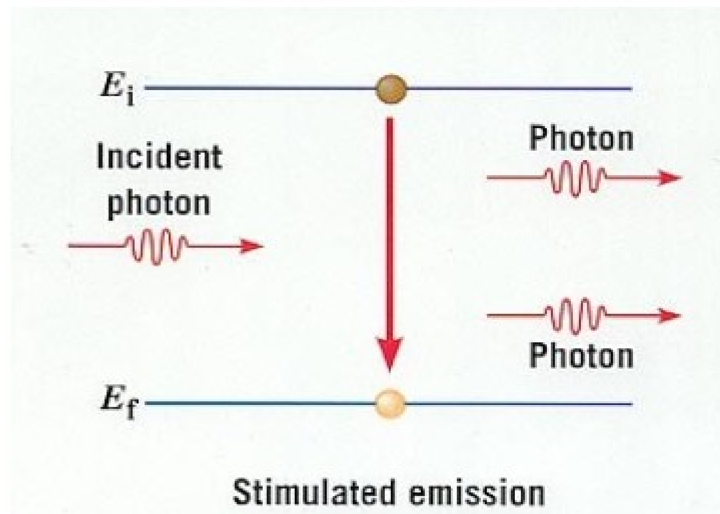
❖ **Einstein's derivation of stimulated emission:**

Einstein's view on radiation law and derivation of A and B coefficients.

"On the Quantum Mechanics of Radiation"



Spontaneous Emission



Stimulated Emission

Einstein's theory led to the development of LASERS

Outcomes of Quantum mechanics

- **Theory of solids: (Failure of classical theory)**
  - ✓ Attempts were made to prove Dulong and petit's law
  - ✓ It fails when applied to light elements like carbon at low temperatures
  - ✓ Reason for the failure is assumption of classical theory that a body radiates energy continuously
- **Einstein's theory of specific heat:**
  - ✓ Predicted variation of C_V with temperature accurately
  - ✓ It fails when applied to heavy elements like Al, Cu, etc.,
- **Debye's theory:**
  - ✓ It is a modified Einstein theory
  - ✓ Gave excellent agreement with experiment over whole observable temperature range

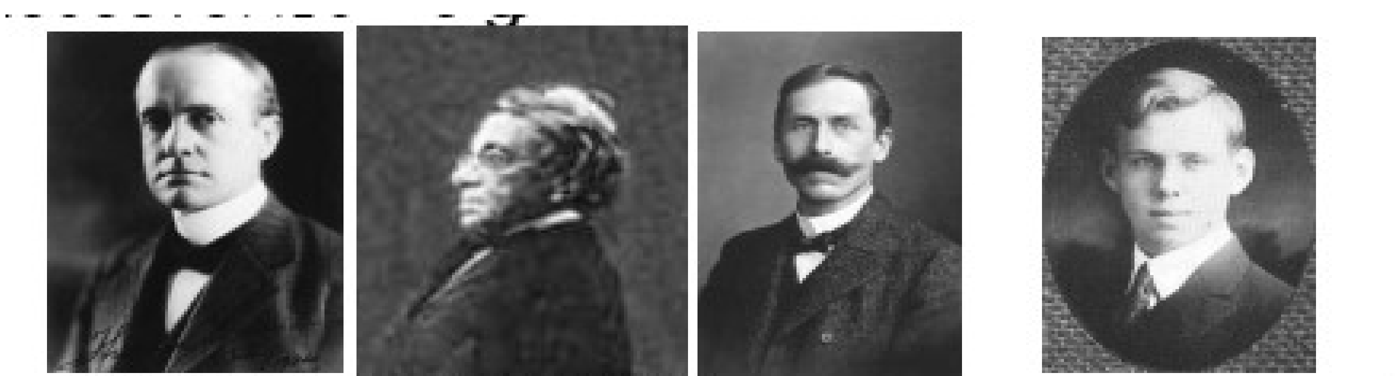
Outcomes of Quantum mechanics

- **Bohr's theory of hydrogen spectrum**

  ✓ Bohr applied Planck's quantum theory to rutherford's model

  ✓ Successfully explained the structure of Hydrogen atom

  ✓ Bohr's series : Lyman, Balmer, Paschen, Brackett and Pfund



Theodore Lyman 1874 - 1954 | *Johan Jakob Balmer* 1825 - 1898 | *Friedric Paschen* 1865 - 1947 | *Frederick Sumner Brackett* 1896 - 1988

Outcomes of Quantum mechanics

1) Concept of stationary orbits – Non-radiating orbits
2) Angular momentum is an integral multiple of $\hbar$
3) Stationary nucleus
4) Non-relativistic motion of electrons - speed of electrons<<<c, so mass of electron is constant
5) Transition – Absorption and emission principles
6) Frequency condition – $h\nu = E_f - E_i$

Outcomes of Quantum mechanics

7) **Franck – Hertz experiment: Predicts excitation and ionisation potentials of an atom.**

8) **Wilson–Sommerfeld quantization rule – successfully predicts the allowed energy values of periodic system**

"Only those orbits are allowed as stationary states for which each phase integral is an integral multiple of h in a complete period"

Outcomes of Quantum mechanics

Applications of Wilson–Sommerfeld quantization rule:

a. Particle in a box

b. The harmonic oscillator

c. Rigid rotator

d. Sommerfeld elliptic orbits

e. Energy of electron

Consolidating results of Quantum Mechanics

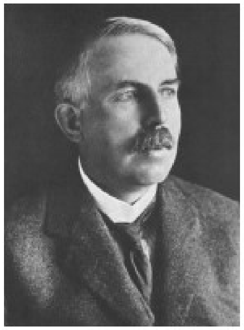
1919: ERNEST RUTHERFORD FINDS THE FIRST EVIDENCE OF PROTONS. HE SUGGESTED IN 1914 THAT THE POSITIVELY CHARGED ATOMIC NUCLEUS CONTAINS PROTONS.

1922: OTTO STERN AND WALTER GERLACH SHOW "SPACE QUANTIZATION"

1923: ARTHUR COMPTON DISCOVERS THE QUANTUM NATURE OF X RAYS, THUS CONFIRMS PHOTONS AS PARTICLES.

1924: LOUIS DE BROGLIE PROPOSES THAT MATTER HAS WAVE PROPERTIES.

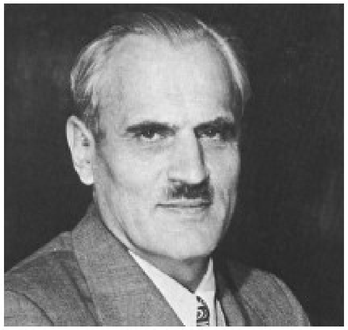
1924: WOLFGANG PAULI STATES THE QUANTUM EXCLUSION PRINCIPLE.



E. RUTHERFORD

OTTO STERN

W. GERLACH



A. COMPTON

L. de BROGLIE

W. PAULI

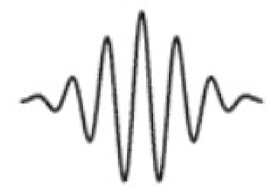
Consolidating results of Quantum Mechanics

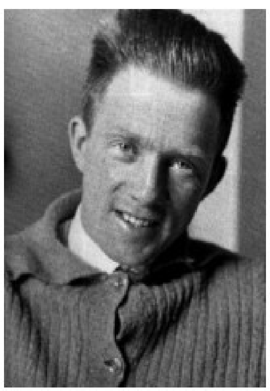
1925: WERNER HEISENBERG, MAX BORN, AND PASCAL JORDAN FORMULATE QUANTUM MATRIX MECHANICS.

1925: SAMUEL A. GOUDSMITH AND GEORGE E. UHLENBECK POSTULATE THE ELECTRON SPIN

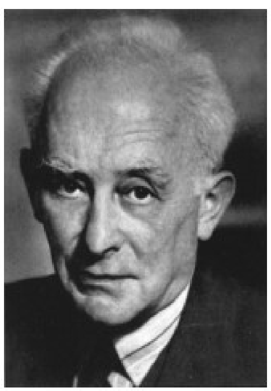
1926: ERWIN SCHRODINGER STAES THE NONRELATIVISTIC QUANTUM WAVE EQUATION AND FORMULATES THE QUANTUM MECHANICS. HE PROVES THAT WAVE AND MATRIX FORMULATIONS ARE EQUIVALENT

Wave Function





W. HEISENBERG



MAX BORN

P. JORDAN

S. GOUDSMITH

G. UHLENBECK

E. SCHRODINGER

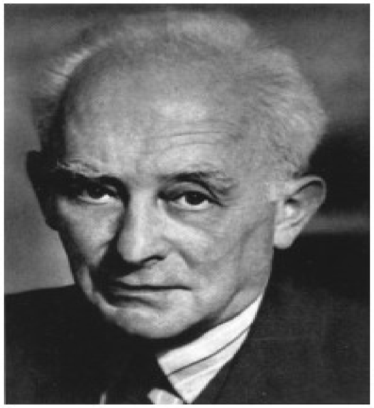
Consolidating results of Quantum Mechanics

1926: ***MAX BORN*** **GIVES A** ***PROBABILISTIC INTERPRATATION*** **OF THE WAVE FUNCTION.**

1927: ***WERNER HEISENBERG*** **STATES THE** ***QUANTUM UNCERTAINTY PRINCIPLE.***

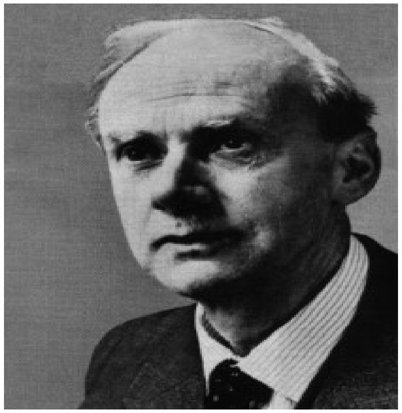
1928: ***PAUL DIRAC*** **STATES HIS** ***RELATIVISTIC QUANTUM WAVE EQUATION.*** **HE PREDICTS THE EXISTENCE OF THE** ***POSITRON.***

1932: JHON von NEUMANN WROTE "THE FOUNDATION OF QUANTUM MECHANICS"



MAX BORN

W. HEISENBERG



PAUL DIRAC

J. von NEUMANN