ATOM

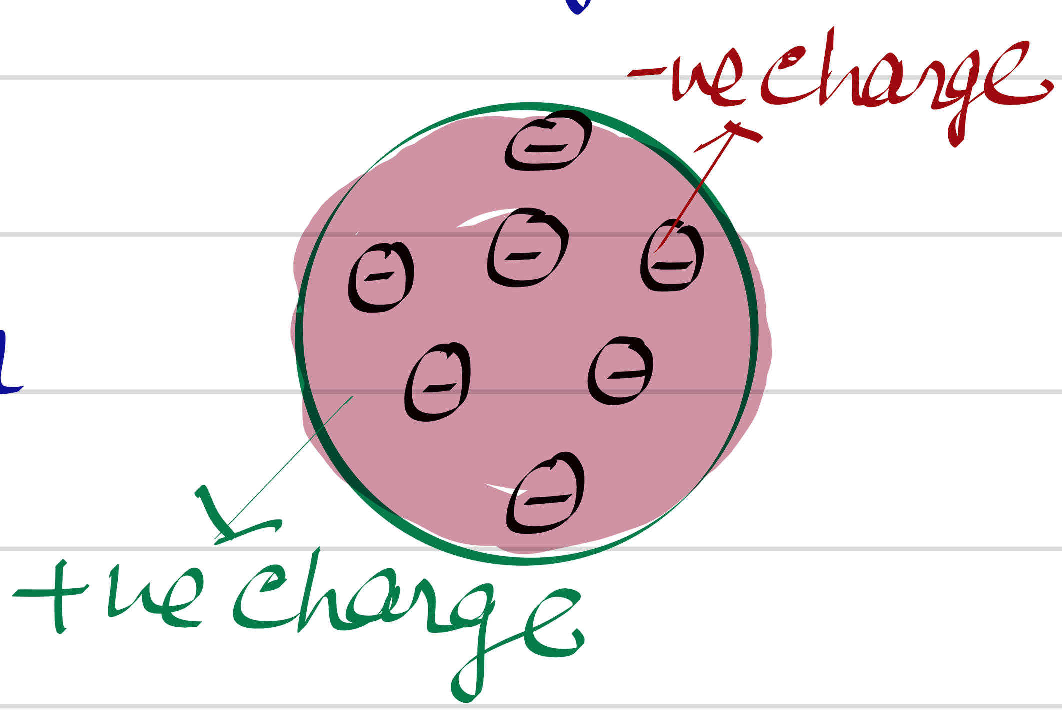
Ch. 12

Thomson's Model of Atom

{First atomic model}

According to this model of atom the +ve charge of the atom is uniformly distributed throught the volume of the atom and the negatively charged electrons are embedded in it like seeds in watermelon or plums in pudding.

* According to this model atoms are spherical.
* This model also known as 'plum pudding model'.



Limitations

(i) It could not explain atomic spectra.

(ii) It could not explain large angle deflection of α particles.

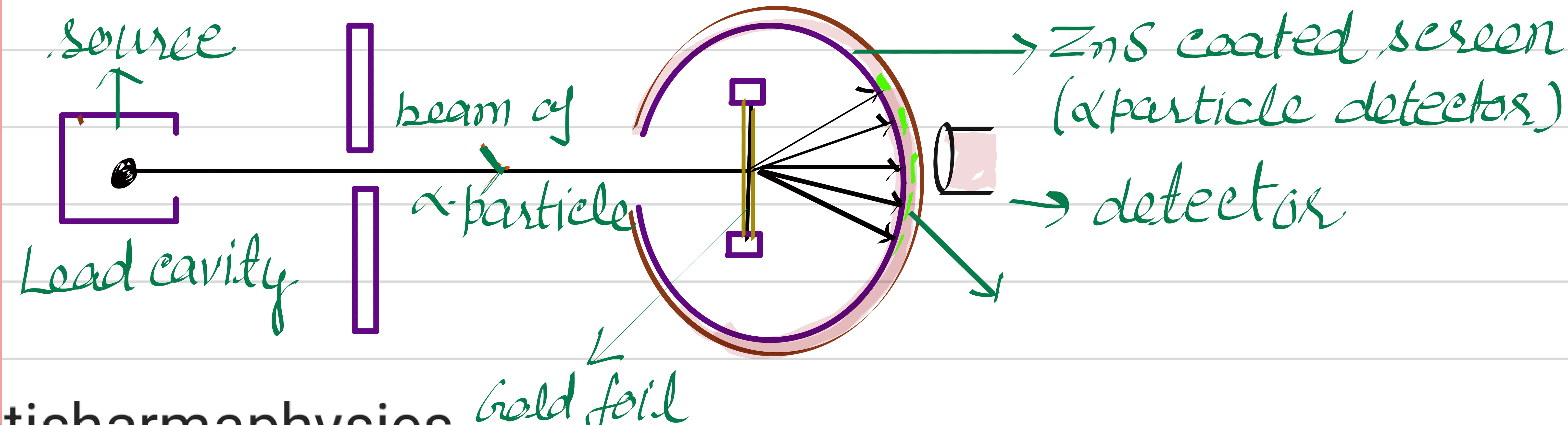
(iii) It lacked the concept of a central nucleus.

Rutherford's α-Scattering Experiment

Geiger-Marsden's α scattering experiment

Rutherford and his two associates: Geiger and Marsden performed an experiment of α scattering. Main point of this experiments are:

- A thin sheet of gold foil was bombarded with α particles (helium nuclei).



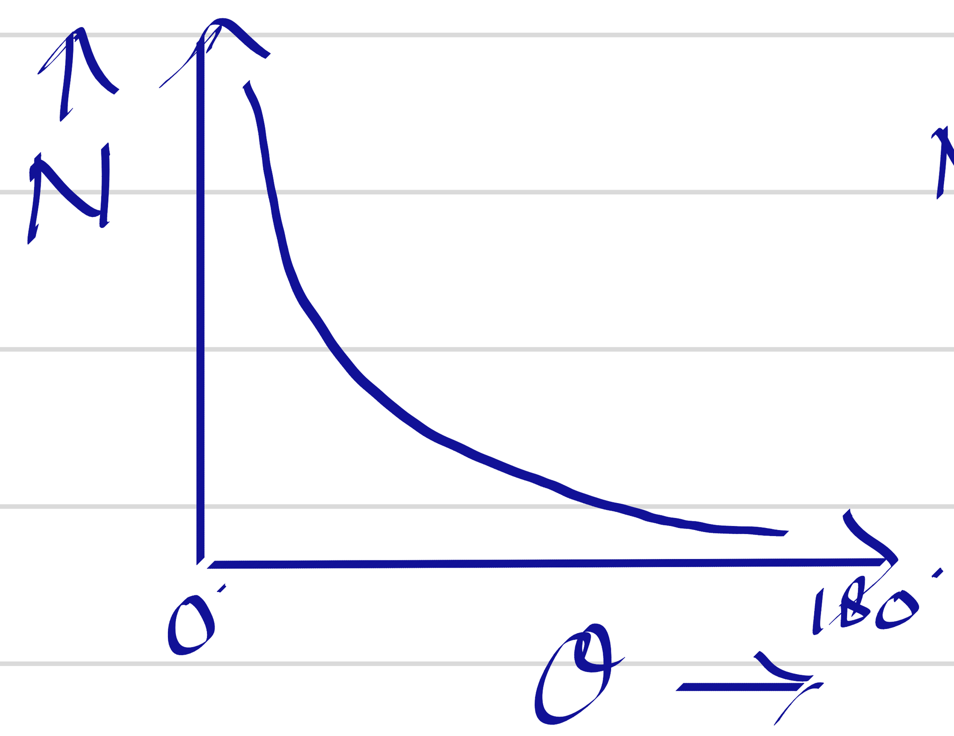
Observations

(i) Most of the particles passes through the foil without any deflection. (straight)

(ii) Some particles were slighly deflected.

(iii) A very small number of α-particles (about 1 in 8000) retraced their path. (deflected 180°)

(iv) Graph b/w total number of α particles scattered and scattering angle θ



N → No. of α particles

θ → scattering angle

Conclusions

(i) Most of the space in atom is empty.

(ii) the charge is concentrated in the central of atom called nucleus.

(iii) Coulomb's force is applied between α particle and nucleus.

(iv) Deflection shows the repulsion between α particle and nucleus.

(v) Electrons are very light and do not affect the motion of α particles.

Alpha Particle Trajectory and Impact Parameter

The shape of trajectory of scattered α particles depends on the impact parameter and nature of the potential field.

Impact Parameter (b):

The perpendicular distance of the velocity vector of the α-particle from the centre of the nucleus, when it is far away from the atom.

b → Impact parameter
θ → scattering angle

* Impact parameter has inverse-square law character. Therefore for larger b, the repulsive force on α particles is less.
* For large impact parameter, scattering angle θ is small.
* At a certain distance 'r_0', α-particle retraces its path i.e scattered at 180°. This distance is called <u>distance of closest approach (r_0)</u>

By conservation of energy at the distance of closest approach the kinetic energy of the α particle is converted into potential energy.

i.e. $$K = U$$

$$\frac{1}{2}mv^2 = k\frac{q_1q_2}{r}$$

$$= \frac{k(2e)(Ze)}{r_0}$$

or $$\frac{1}{2}mv^2 = \frac{2kZe^2}{r_0}$$

or $$\boxed{r_0 = \frac{4kZe^2}{mv^2} \simeq 10^{-15}m \text{ or } 1 \text{ fermi}}$$

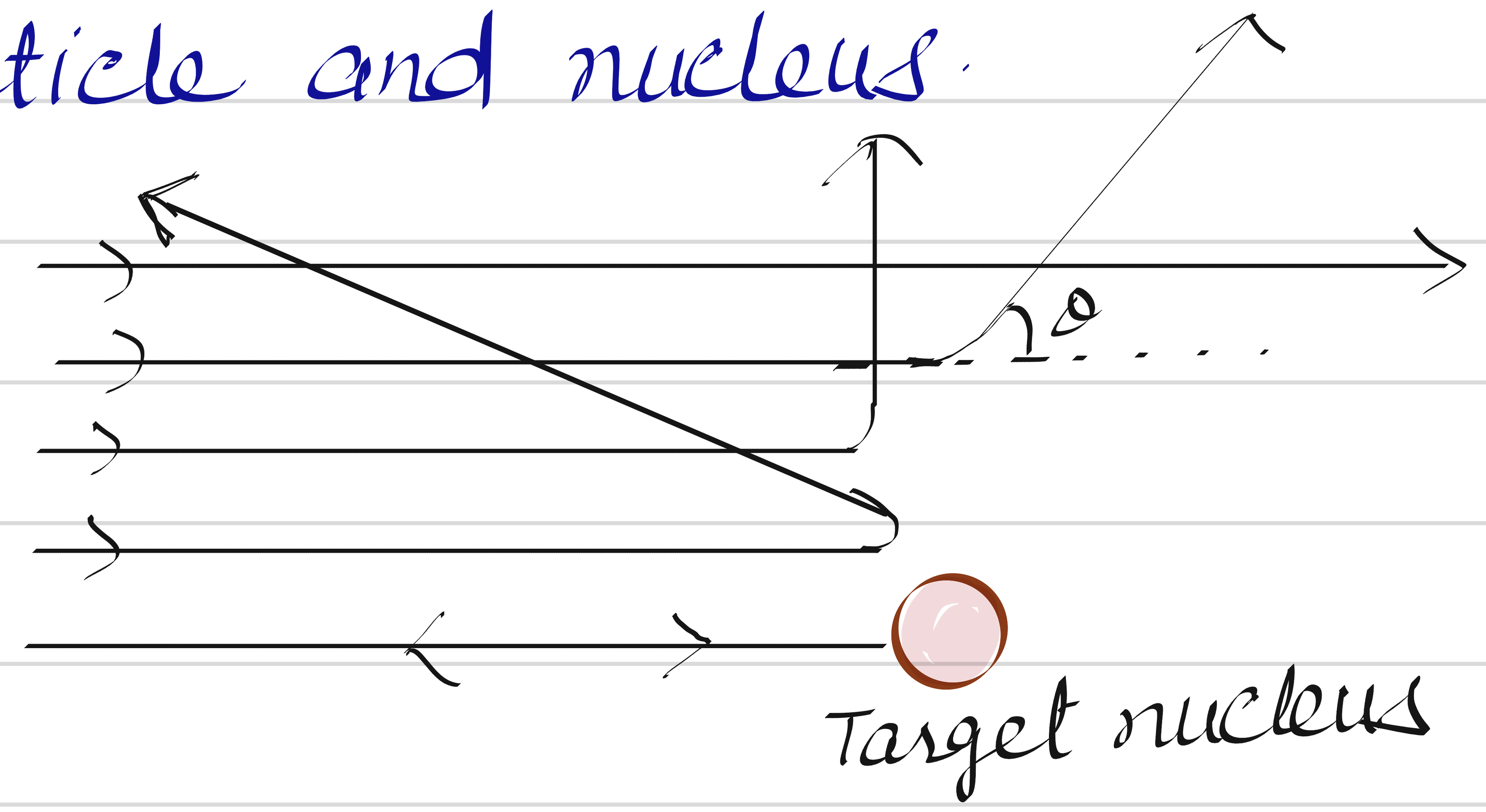
here $K = \frac{1}{4\pi\epsilon_0} = 9\times10^9\ Nm^2/C^2$, $\frac{1}{2}mv^2 = 7.7\ eV$

Alpha-Particle Trajectory:

Trajectory of an α-particle can be determined using Newton's second law and coulomb's law for electrostatic repulsion between the α-particle and positively charged nucleus.

$$F = \frac{1}{4\pi\epsilon_0}\frac{(2e)(Ze)}{r^2}$$

$r \rightarrow$ distance b/w α particle and nucleus.



Electron orbits According to Rutherford model electrons revolve nucleus in dynamically stable orbits. Thus for a stable orbit in hydrogen atom centripetal force is provided by electrostatic force,

$$F_e = F_c$$

$$\frac{1}{4\pi\epsilon_0}\cdot\frac{e^2}{r^2} = \frac{mv^2}{r}$$

or $\boxed{r = \frac{e^2}{4\pi\epsilon_0 mv^2}} \Rightarrow \boxed{v^2 = \frac{e^2}{4\pi\epsilon_0 mr}}$

Kinetic energy 'K' and electrostatic potential energy 'U' of electron,

$$K = \frac{1}{2}mv^2 = \frac{1}{2}\cancel{m}\frac{e^2}{4\pi\epsilon_0 \cancel{m}r} \Rightarrow \boxed{K = \frac{e^2}{8\pi\epsilon_0 r}}$$

and $\boxed{U = -\frac{1}{4\pi\epsilon_0}\frac{e^2}{r}}$ $\left[\because U = -\frac{1}{4\pi\epsilon_0}\frac{q_1q_2}{r}\right]$

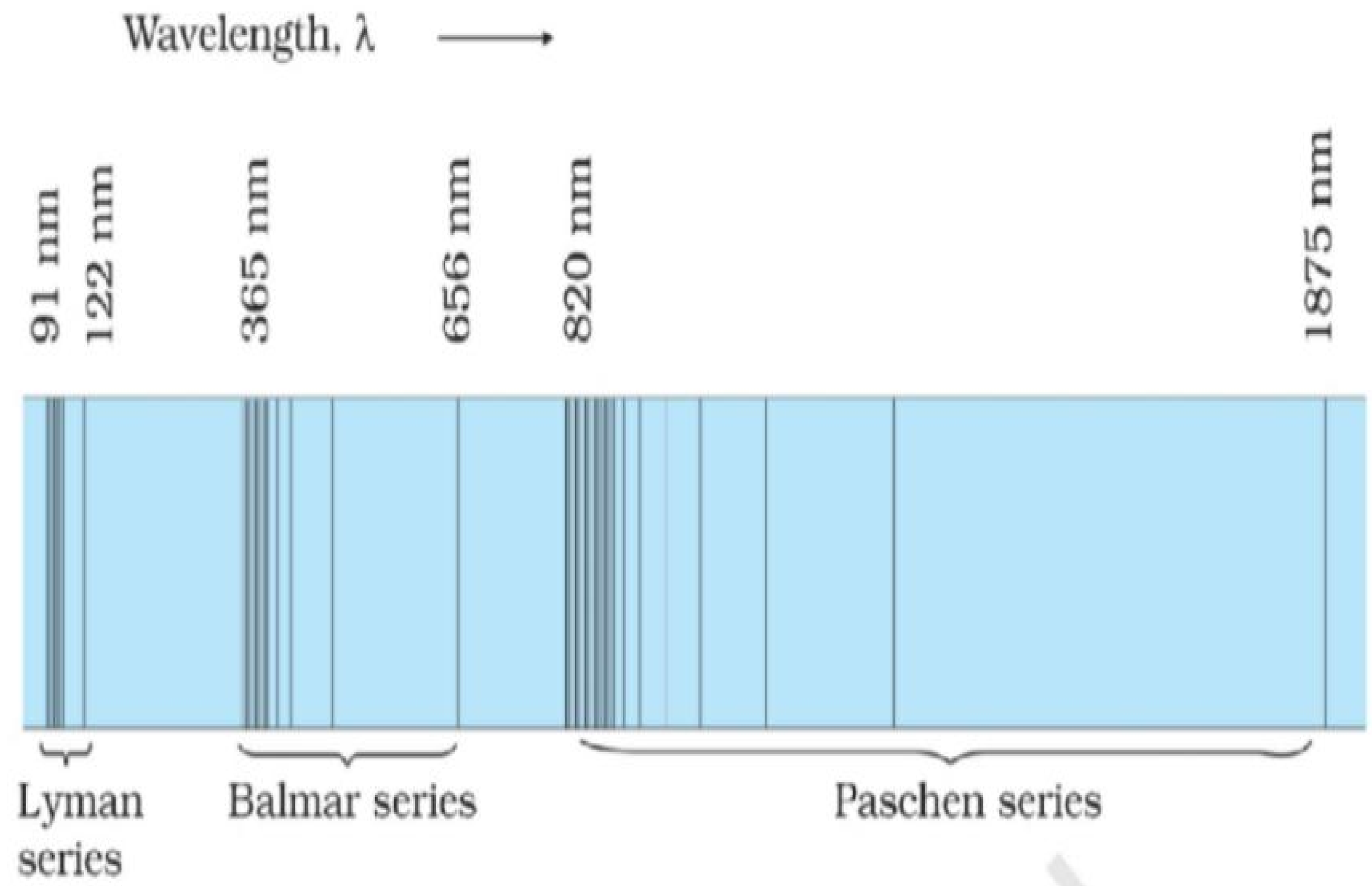
(-ve sign shows that F_e is in the dir^n of $-r$)

Total energy: Total energy of electron, $E = K + U$

$$E = \frac{e^2}{8\pi\varepsilon_0 r} - \frac{e^2}{4\pi\varepsilon_0 r}$$

or $$\boxed{E = -\frac{e^2}{8\pi\varepsilon_0 r}}$$

-ve sign shows electron is bound to the nucleus.



Hydrogen Spectrum emission lines

Atomic Spectra

Each element has a characterstic spectrum of radiation, which it emits.

Atomic Spectrum: When an electron absorbs energy its electrons jump to higher energy levels and when falls back to lower energy levels, the emit light of specific wavelengths and creat atomic spectrum.

Hydrogen Atom: The simplest atom with one electron and one proton, crucial to understand atomic structure

Energy Levels: In hydrogen, electrons occupy distinct energy levels ($n = 1, 2, 3$). The energy difference between these levels determines the wavelength of light emitted.

Emission Spectrum: When an electron in hydrogen returns to lower energy level, it emits light. The emitted light is observed as discrete lines at specific wavelengths, known as emission spectrum

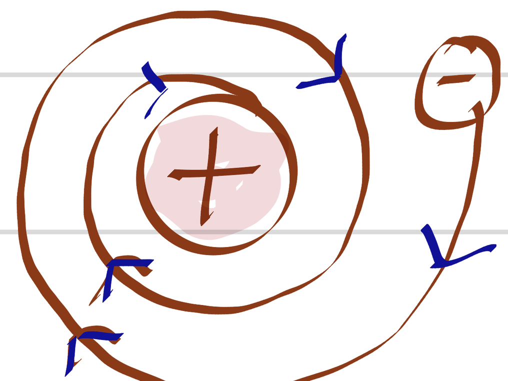
Absorption Spectrum: When light passes through hydrogen gas, certain wavelengths are absorbed as electrons jump to higher energy levels. The absorbed wavelengths show up as dark line in the spectrum, known as absorption Spectrum.

Limitations of Rutherford's Atomic Model:

(I) Rutherford model cannot explain the stability of an atom. Electron should lose energy and crash into the nucleus, but this does not happen.

(II) It could not explain the specific light pattern (spectral lines) seen in atoms.

(III) It did not explain how electrons are arranged around the nucleus.



Spiral path of electron

Bohr's Model:

(I) Every atom consists a central core called nucleus in which entire mass and charge of atom are concentrated.

(II) A suitable numbers of electrons revolve around the nucleus in circular orbits.

(III) Electrons move in fixed orbits around the nucleus

(IV) Each orbit has a specific energy level.

(V) Electrons absorb or emit energy when they jump between the orbits.

(VI) It explained the spectral lines.

Postulates of Bohr's Atomic Model:

1. Electrons in stable orbits - Electrons revolve around the nucleus in certain fixed circular orbits without emitting energy, making atom stable.

2. Quantised angular momentum - The angular momentum of an electron in a given orbit is quantised and some integral multiple of $\frac{h}{2\pi}$.

i.e $$\boxed{L = mvr = \frac{nh}{2\pi}}$$

$n \rightarrow$ +ve integer , $h \rightarrow$ Planck's constant $= 6.6 \times 10^{-34}$ Js

3. <u>Energy absorption or Emission</u>: Electrons absorb or emit energy when they jump between orbits, with energy equal to the difference between two levels.

$$\boxed{E_i - E_f = h\nu}$$

$h \rightarrow$ Planck's constant
$\nu \rightarrow$ frequency of radiation

where E_i and E_f are the energies of initial and final state. $[E_i > E_f]$

<u>Radius of Bohr's stationary orbits</u>-

We know for stationary orbits

$$mvr = \frac{nh}{2\pi}$$

or $$v = \frac{nh}{2\pi mr} \quad — (1)$$

also $$\frac{mv^2}{r} = \frac{kZe^2}{r^2} \quad [\because F_c = F_e]$$

put value of v from eqn (1), we get

$$\frac{m}{r} \times \frac{n^2h^2}{4\pi^2 m^2 r^2} = \frac{kZe^2}{r^2}$$

or $$r = \frac{n^2h^2}{4\pi^2 mkZe^2}$$

For hydrogen atom $Z = 1$, then

$$\boxed{r = \frac{n^2h^2}{4\pi^2 mke^2}}$$

It shows that $\boxed{r \propto n^2}$

Hence radius of stationary orbits are in the ratio $1^2 : 2^2 : 3^2 \ldots$ i.e $1:4:9 \ldots$

Clearly stationary orbits are not equally spread.

<u>Velocity of electron in Bohr's stationary orbit</u> -

As we know

$$\frac{mv^2}{r} = \frac{kZe^2}{r^2}$$

or $$r = \frac{kZe^2}{mv^2} \quad -(1)$$

also by $$mvr = \frac{nh}{2\pi}$$

$$r = \frac{nh}{2\pi mv} \quad -(2)$$

from (1) and (2)

$$\frac{kZe^2}{mv^{\cancel{2}}} = \frac{nh}{2\pi \cancel{m}v}$$

or $$\boxed{v = \frac{2\pi kZe^2}{nh}} \Rightarrow \boxed{v = \frac{2\pi ke^2}{nh}}$$

→ for hydrogen $Z=1$

here, $v \propto \frac{1}{n}$. i.e orbital velocity of electron in outer orbits is smaller as compared to inner orbits.

<u>Frequency of electron in Bohr's stationary orbit:</u>

Frequency of electron is the number of revolution completed by electron in one second.

As $v = r\omega$

$= r(2\pi\nu)$ $\qquad \nu \to$ frequency

@jyotisharmaphysics

or $\quad \nu = \frac{v}{2\pi r}$

$$= \frac{\cancel{2\pi} kZe^2/nh}{\cancel{2\pi} r}$$

$$\nu = \frac{kZe^2}{nhr}$$

For hydrogen $Z=1$, then

$$\nu = \frac{ke^2}{nhr}$$

here $\nu \propto \frac{1}{n}$, ie frequency of electron in subsequent orbit is smaller.

<u>Total energy of electron in the stationary state of hydrogen atom</u>

Radius of nth possible orbit

$$r_n = \frac{n^2h^2}{4\pi^2 m ke^2} \qquad n = 1, 2, 3 \ldots$$

put $k = \frac{1}{4\pi\epsilon_0}$

then $\quad r_n = \frac{n^2h^2}{4\pi^2 m \times \frac{1}{4\pi\epsilon_0} e^2}$

$$r_n = \frac{n^2}{m} \cdot \left(\frac{h}{2\pi}\right)^2 \cdot \frac{4\pi\epsilon_0}{e^2} \quad \text{---} ①$$

Now the total energy

$$E_n = \frac{-e^2}{8\pi\epsilon_0 r_n}$$

put the value of r_n from eqn ①, we get

$$E_n = \frac{-e^2 \times m \cancel{4\pi^2} e^2}{8\cancel{\pi}\epsilon_0 \, n^2 h^2 \, \cancel{4\pi}\epsilon_0}$$

$$\boxed{E_n = -\frac{me^4}{8n^2\epsilon_0^2 h^2}}$$

Substituting values, we get

$$E_n = \frac{2.18 \times 10^{-18}}{n^2} \, J$$

or $\boxed{E_n = \frac{13.6}{n^2} \, eV}$ $[1 \, eV = 1.6 \times 10^{-19} J]$

$[n \rightarrow$ Principal quantum number$]$

-ve sign shows that electron is bound to nucleus.

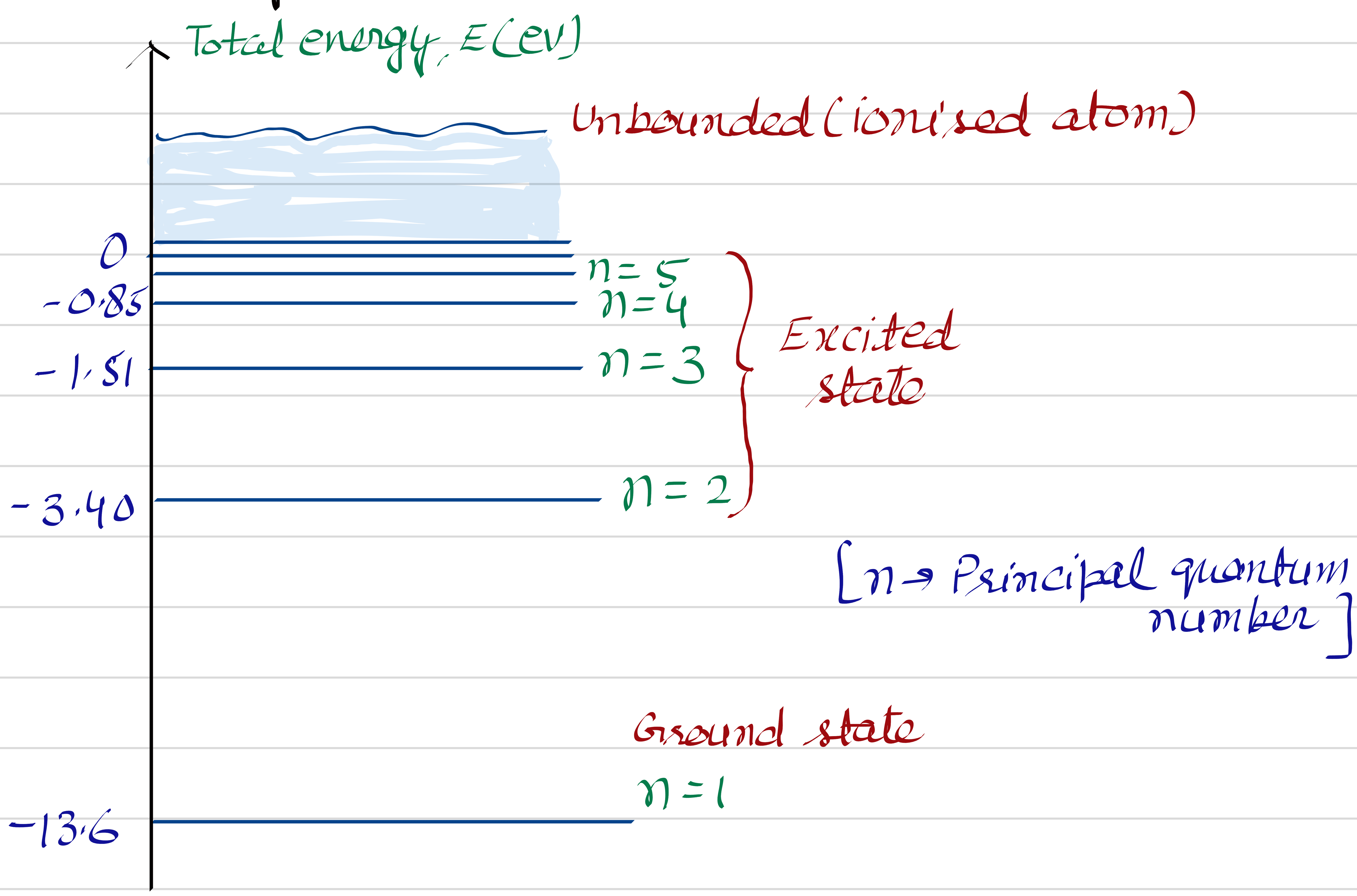
* The energy of an atom is the least (largest -ve value) when its electron is revolving in an orbit closest to the nucleus.

<u>Energy levels</u>: Electron in an atom occupy specific regions called energy levels or shells. These levels are quantized, means electrons can exist in certain energy states.

<u>Ground state</u>: The lowest energy level is called the ground state. It is the most stable state.

<u>Excited State</u>: When at electron absorb energy, it jumps to a higher energy level, known as the excited state. This state is unstable and the electron eventually fall back releasing energy as light.

Energy level diagram for the hydrogen atom in stationary state



* The highest energy state corresponding to $n = \infty$ and has energy of 0 eV. This the energy when electron is completely removed ($r = \infty$)
* Energies of the excited state come closer as n increases.

Line Spectra of hydrogen atom

- Emission Spectrum produces when electron drops to lower energy level, emitting light a specific wavelengths.
- Discrete lines: Only certain wavelengths appear, as electrons occupy quantised energy levels.

@jyotisharmaphysics

• Spectral Series -

→ **Lymen Series** : Transition to the $n=1$ level in UV region

→ **Balmer Series**: Transition to the $n=2$ level in the visible region.

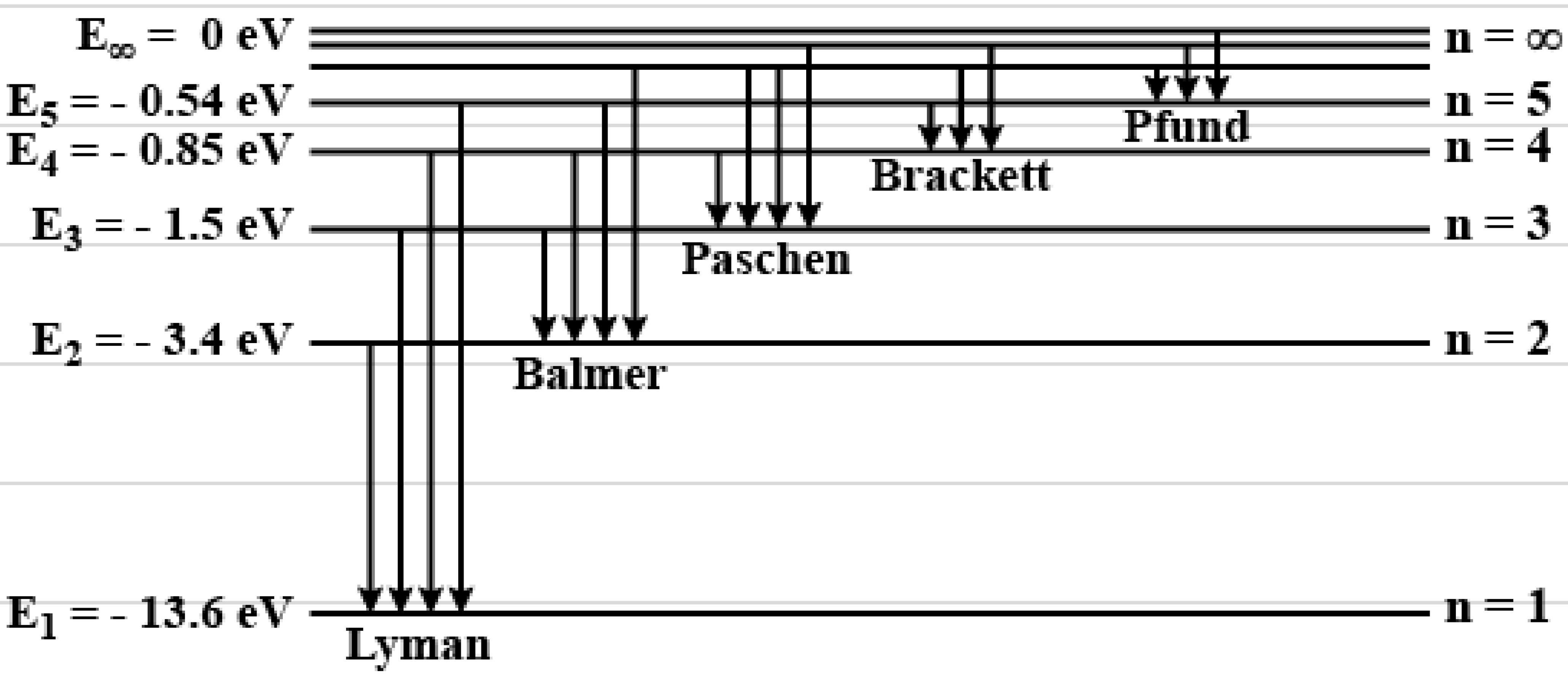
→ **Paschen, Brackett and Pfund Series**: Transition to $n=3$, $n=4$, and $n=5$, respectively, in the infrared region.

→ Rydberg Formula :

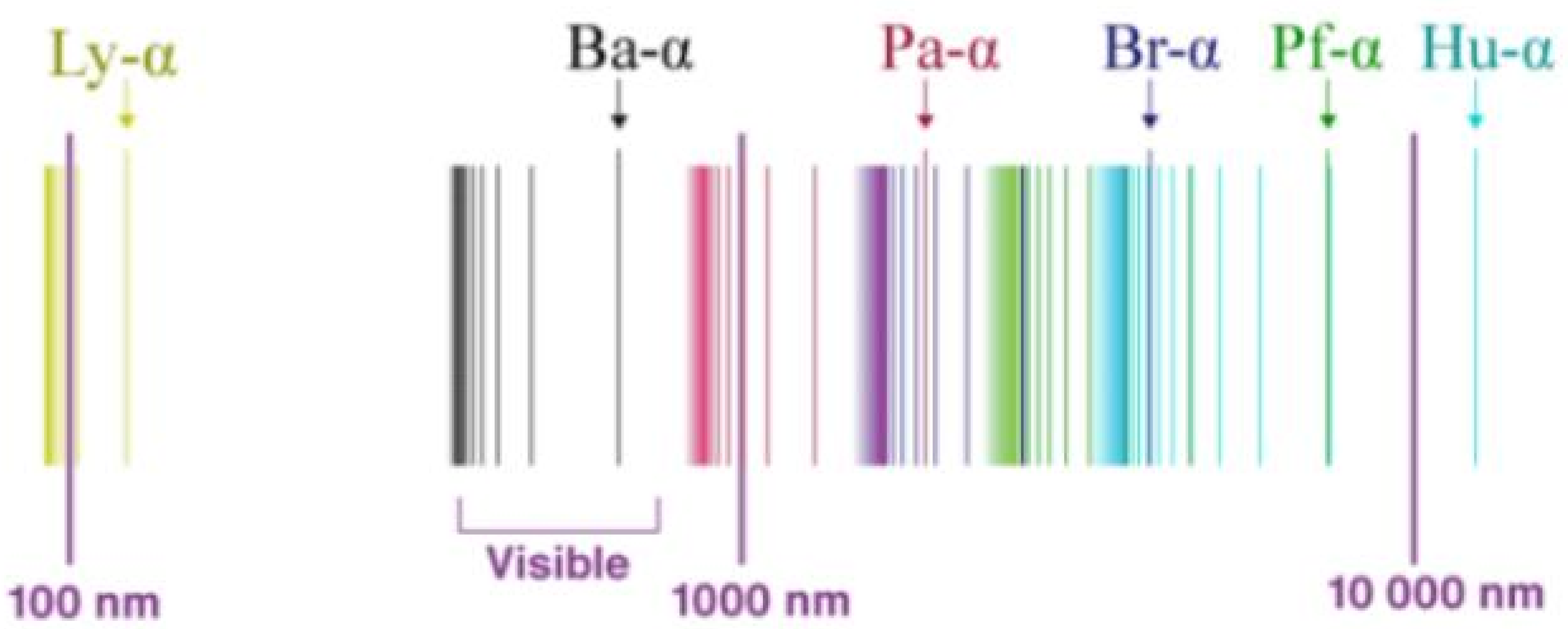
$$\frac{1}{\lambda} = R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right)$$

where $R = 1.097 \times 10^{7}\ m^{-1}$

also $E = h\nu = \frac{hc}{\lambda}$ $[c = \nu\lambda]$



Energy level diagram for hydrogen atom



Ionisation Energy: Amount of energy required to remove an electron from an isolated atom or molecule

@jyotisharmaphysics

Multiple Choice Questions (1 Mark each)

Q.1 In Bohr's theory of model of hydrogen atom, name the physical quantity which equals to an integral multiple of $h/2\pi$?

(a) Momentum (b) Angular momentum

(c)Angular frequency (d)Angular velocity

Q.2 What is the relation between 'n' and radius 'r' of the orbit of electron in hydrogen atom according to Bohr's theory?

(a) 'r' is directly proportional to n (b) 'r' is directly proportional to n^2

(c) 'n^2' is directly proportional to r (d) 'r' is inversely proportional to n^2

Q.3 What is Bohr's frequency condition?

(a) $h\nu=E_i-E_f$ (b) $h\nu= E_f-E_i$ (c) $h\nu=E-E_f$ (d) $h=E_i-E_f$

Q.4 Write the expression for Bohr's radius in hydrogen atom?

(a) $r=4\Pi E_0 \times h^2/4\pi^2 me$ (b) $r=4\Pi E_0 \times h^2/4\pi^2 me^2$

(c) $r=4\Pi E_0 \times h^2/4\pi me^2$ (d)) $r=4\Pi E_0 \times h/4\pi^2 me^2$

Q.5 Name the spectral series of hydrogen atom lying in visible region?

(a) Paschen series (b)Pfund series (c)Bracket series (d) Balmer series

Q.6 The total energy of an electron in 1st excited state of hydrogen atom is about -3.4eV. What is the kinetic energy of electron in this state?

(a) -3.4 eV (b) 3.4 eV (c) 0.34 eV (d) -0.34 eV

Q7. Which of the following spectral series in hydrogen atom gives spectral line of 4860 ^{0}A?

(a)Lyman (b) Balmer (c) Paschen (d) Brackett

Q.8 When hydrogen atom is in first excited level, its radius is

(a)same (b) half (c) twice (d) 4 times

Q.9 Rutherford model of atom was unstable because

(a)nuclei will break down (b)electron move in circular orbit

(c)orbiting electrons radiate energy (d) electrons are repelled by the nucleus

Assertion –Reason type questions(1 mark each)

Answer: A Both are correct and reason is correct explanation of assertion.

Answer: B Both are correct but reason is not the correct explanation of assertion.

Answer: C Reason is wrong.

Answer: D Both are wrong.

Q10. **Assertion:** According to Bohr's atomic model the ratio of angular momenta of an electron in first excited state and in ground state is 2:1.

Reason: In a Bohr's atom the angular momentum of the electron is directly proportional to the principal quantum number.

Q11. **Assertion:** The positively charged nucleus of an atom has a radius of almost 10^{-15}m.

Reason: In a-particle scattering experiment, the distance of closest approach for particles is ≃ 10^{-15}m.

Q12. **Assertion:** For the scattering of a-particles at a large angles, only the nucleus of the atom is responsible.

Reason: Nucleus is very heavy in comparison to α particle.

Q13.**Assertion**: Bohr had postulated that the electrons in stationary orbits around the nucleus do not radiate

Reason: According to classical physics all moving electrons radiate.

Q14. **Assertion:** Atoms are not electrically neutral.

Reason: Number of protons and electrons are different.

MCQs - Answers

1.(b) Angular momentum

2. (b)'r' is directly proportional to n^2

3.(b) $h\nu=E_f-E_i$

4. (b) $r=4\Pi E_0 \times h^2/4\pi^2 me^2$

5. (d) Balmer series

6. (b) kE=-E =-(-3.4)=3.4 eV

7. (b) Balmer

8. (d) 4 times

9. (c)orbiting electrons radiate energy

Assertion and Reason- Answers

10. Correct answer: A

11. Correct Answer: A

12. Correct Answer: A

13. Correct Answer: B

14. correct Answer D