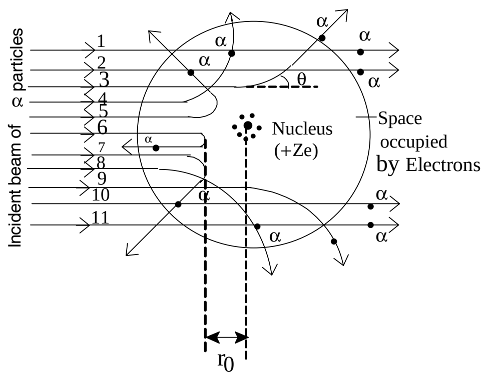
ATOMS AND NUCLEI
ATOMIC MODELS

I. Observations of Alpha particle scattering experiment:

(a) Most of the α-particles were found to pass through the gold- foil without being deviated from their paths.

(b) Some α-particles were found to be deflected through small angles $\theta < 90°$.

(c) Few α-particles were found to be scattered at fairly large angles from their initial path $\theta > 90°$



d) A very small number of α-particles about 1 in 8000 practically retracted their paths or suffered deflections of nearly 180° (e.g particle 6 in figure.)

(i) The observation (a) indicates that most of the portion of the atom is hollow inside.

(ii) Because α-particle is positively charged, from the observations (b) and (c) atom also have positive charge and the whole positive charge of the atom must be concentrated in small space which is at the centre of the atom is called nucleus. The remaining part of the atom and electrons are revolving around the nucleus in circular objects of all possible radii. The positive charge present in the nuclei of different metals is different . Higher the positive charge in the nucleus, larger will be the angle of scattering of α-particle.

e) **Distance of Closest Approach :**

Kinetic energy of the α-particle

$$K = \left(\frac{1}{2}\right) m_\alpha v^2{}_\alpha$$

Because the positive charge on the nucleus is Ze and that on the α-particle 2e, hence the electrostatic potential energy of the α-particle, when at a distance r_0 from the centre of the nucleus, is given by

$$U = \frac{1}{4\pi\in_0} \cdot \frac{(2e)(Ze)}{r_0}$$

Because at $r = r_0$ kinetic energy of the particle appears as its potential energy, hence, K=U

$$\frac{1}{4\pi\in_0} \cdot \frac{(2e)(Ze)}{r_0} = \frac{1}{2} m_\alpha v_\alpha^2$$

$$r_0 = \frac{1}{4\pi\in_0} \frac{4Ze^2}{m_\alpha v_\alpha{}^2}$$

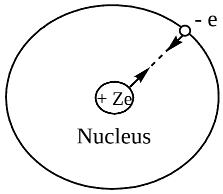
Above equation shows that for a given nucleus, the value of r_0 depends upon the initial kinetic energy of the α-particle.

II. BOHR'S MODEL

On the basis of quantum theory Bohr modified Rutherford's atomic model and gave the following postulates to explain the observed facts.

(a) Electron can revolve round the nucleus only in certain allowed orbits called stationary orbits and the Coulomb's force of attraction between electron and the positively charged nucleus provides necessary centripetal force.

$$\frac{k(Ze)e}{r^2} = \frac{mV^2}{r}$$



(b) Suppose m is the mass of electron, V is the velocity and 'r' is the radius of the orbit, then in stationary orbits the angular momentum of the electron is an integral multiple of $\frac{h}{2\pi}$, where h is the Planck's constant. The angular momentum $L = I\omega = mVr = n\frac{h}{2\pi}$ where n=1,2,3,4…. called principal quantum number.

(c) An electron in a stationary orbit has a definite amount of energy. It posses kinetic energy because of its motion and potential energy on account of the attraction of the nucleus. Each allowed orbit is therefore associated with a certain quantity of energy called the energy of the orbit, which equals the total energy of the electron in it. In these allowed orbits electrons revolve without radiating energy .

(d) Energy is radiated or absorbed when an electron jumps from one stationary orbit to another stationary orbit. This energy is equal to the energy difference between these two orbits and emitted or absorbed as one quantum of radiation of frequency given by Planck's equation . This is called Bohr's frequency condition.

(e) **Radius of Bohr's orbit :** When mass of the nucleus is large compared to revolving electron, then electron revolves around the nucleus in circular orbit.

According to first postulate

$$\frac{k(Ze)e}{r^2} = \frac{mV^2}{r} \left(where \;\; k = \frac{1}{4\pi\epsilon_0} \right) ....(1)$$

According to second postulate

$$mVr = n\frac{h}{2\pi} \text{ where } n = 1,2,3,4............$$

$$\text{(or) } V = \frac{nh}{2\pi mr} \;\; ....\;(2)$$

After solving the equations, radius of the orbit

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

For n^{th} orbit $r_n = \frac{h^2}{4\pi^2 ke^2}.\left(\frac{n^2}{mZ}\right)$ ....(3)

For hydrogen atom Z = 1, radius of the first orbit (n = 1) is given by

$r_1 = 0.529 \times 10^{-10} m \simeq 0.53 Å$

This value is called as Bohr's radius and the orbit is called Bohr's orbit.

In general, the radius of the nth orbit of a hydrogen like atom is given by

$$r_n = 0.53 \left(\frac{n^2}{Z} \right) Å \quad where\, n = 1, 2, 3, ... \quad (4)$$

(f) **Velocity of the Electron in the orbit :**

The velocity of an electron in nth orbit $V_n = \frac{nh}{2\pi m r_n}$

hence $V_n = \frac{2\pi k e^2}{h} . \left(\frac{Z}{n} \right) \left(\therefore r_n = \frac{n^2 h^2}{4\pi^2 k Z m e^2} \right)$ ..(5)

i.e the velocity of electron in any orbit is independent of the mass of electron. The above equation can also be written as

$$\therefore V_n = \left(\frac{c}{137} \right) . \frac{Z}{n} \quad m/s \quad .... (6)$$

Where 'c' is the speed of light in vacuum.

(g) **Time period of electron in the orbit :**

Angular velocity of electron in nth orbit $\omega_n = \frac{V_n}{r_n} = \frac{\omega_0 Z^2}{n^3}$,

where $\omega_0 = \frac{8\pi^3 k^2 e^4 m}{h^3}$ ......(7) is the angular velocity of electron in first Bohr's orbit. The time period of rotation of electron in nth orbit $T = \frac{2\pi}{\omega_n} = \frac{n^3}{2\pi \omega_0 Z^2}$ .... (8) i.e .

$$T \propto \frac{n^3}{Z^2}$$

The time period of rotation increases as n increases and is independent of the mass of the electron.

h) **Energy of the electron in the orbit :**

The kinetic energy of the electron revolving round the nucleus in nth orbit is given by

$$K_n = \frac{1}{2} m V^2 = \frac{1}{2} m \left[\frac{2\pi k e^2}{h} . \frac{Z}{n} \right]^2$$

$$K_n = \frac{2\pi^2 k^2 e^4}{h^2} . \left(\frac{m Z^2}{n^2} \right) ....(9)$$

$$K_n \, \alpha \frac{m Z^2}{n^2}$$

If the reference level (zero potential energy level) is at infinity then the electrostatic potential energy is given by

$$U_n = -\frac{k(Ze)e}{r_n} = -kZe^2 \left[\frac{4\pi^2 k m Z e^2}{n^2 h^2} \right]$$

$$U_n = -\frac{4\pi^2 k^2 e^4}{h^2}\left(\frac{mZ^2}{n^2}\right) \text{.......} \ (10)$$

Total energy of the electron in n^{th} orbit

$$E_n = K_n + U_n = -\frac{2\pi^2 k^2 m Z^2 e^4}{n^2 h^2}$$

$$E_n = -\frac{2\pi^2 k^2 e^4}{h^2}\left(\frac{mZ^2}{n^2}\right) \text{........} \ (11)$$

The expression of total energy for hydrogen like atom may be simplified as

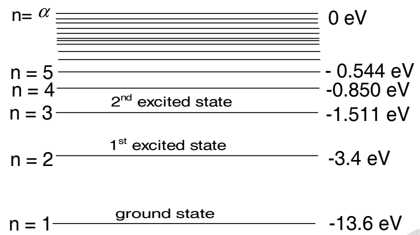
$$E_n = -13.6\frac{Z^2}{n^2} \quad eV \text{ , n = 1,2,3..... } (12)$$

Where -13.6 eV is the total energy of the electron in the ground state of an hydrogen atom.
From the equations (9),(10)&(11) it is clear that

PE : K.E : T.E = -2 : 1 : -1

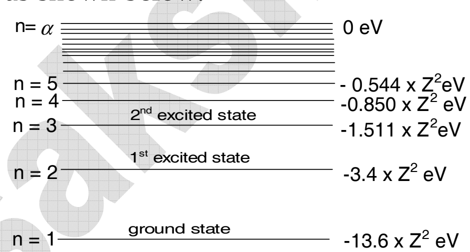
i.e and E = -K (or) E = -K = U / 2

The state n = 1 is called ground state and n > 1 states are called excited states. When electron go from lower orbit to higher orbit speed and hence kinetic energy decrease, but both potential energy and total energy increases. $E \alpha \frac{1}{n^2}$ tells us that the energy gap between the two successive levels decreases as the value of n increases. At infinity level the total energy of the atom becomes zero.



Energy level diagram of hydrogen atom (Z = 1) for normal and excited states as shown the above figure.

The energy level diagram of hydrogen like atom with atomic number Z for normal and excited states as shown below.



The total energy of the electron is negative implies the atomic electron is bound to the nucleus. To remove the electron from its orbit beyond the attraction of the nucleus, energy must be required.

The minimum energy required to remove an electron from the ground state of an atom is called its ionization energy and it is 13.6 Z^2 eV.

In hydrogen atom the ground state energy of electron is –13.6 eV, so 13.6 eV is the ionization energy of the Hydrogen atom.

III. EMISSION OF RADIATION:

When an electron jumps from higher energy level n_2 to a lower energy level n_1 in stationary atom, the difference in energy is radiated as a photon whose frequency ν is given by Planck's formula.

$$E_{n_2} - E_{n_1} = h\nu$$

(or) $h\nu = E_2 - E_1 = 13.6Z^2\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]\ e.V$

$$\left(\therefore E_n = -\frac{13.6Z^2}{n^2}\ e.V\right)$$

since $1eV = 1.6\times10^{-19}\,J$

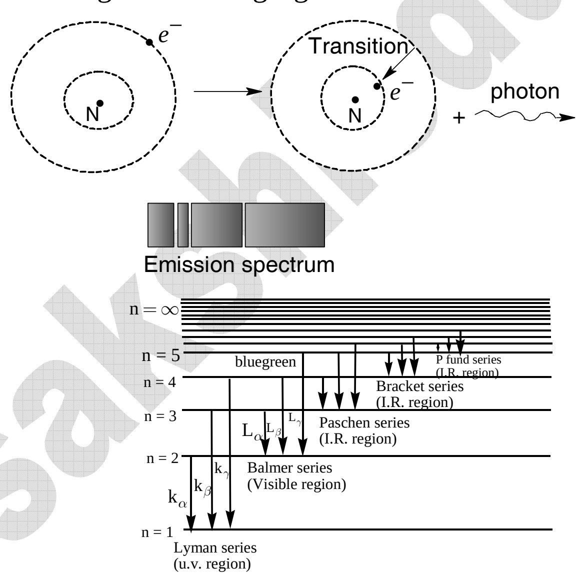
hence

(or) wave number $\bar{\nu} = \frac{1}{\lambda} = RZ^2.\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]\ m^{-1}$

where R is called for "Rydberg constant", when the nucleus is infinitely massive as compared to the revolving electron. In other words the nucleus is considered to be stationary. The numerical value of R is $1.097\times10^{7}\ m^{-1}$.

IV. EMISSION SPECTRUM OF HYDROGEN ATOM :

Electron in hydrogen atom, can be in excited state for very small time of the order of 10^{-8} second. This is because in the presence of conservative force system particles always try to occupy stable equilibrium position and hence minimum potential energy, which is least in ground state. Because of instability, when an electron in excited state makes a transition to lower energy state, a photon is emitted. Collection of such emitted photon frequencies is called an emission spectrum. This is as showing in following figure .



The Spectral Series of Hydrogen Atom as shown in the above figure, are explained below.

(a) Lyman Series : Lines corresponding to transition from outer energy levels $n_2 = 2, 3, 4, ...\infty$ to first orbit ($n_1 = 1$) constitute Lyman series. The wave numbers of different lines are given by,

$$\bar{v} = \frac{1}{\lambda} = R\left[\frac{1}{1^2} - \frac{1}{n_2{}^2}\right]$$

(i) Line corresponding to transition from $n_2 = 2$ to $n_1 = 1$ is first line; its wavelength is maximum.

$$\frac{1}{\lambda_{max}} = R\left[\frac{1}{1^2} - \frac{1}{2^2}\right] = 1.1\times10^7\left[\frac{1}{1} - \frac{1}{4}\right]$$

$$\therefore \lambda_{max} = 1212Å$$

Similarly transition from $n_2 = \infty$ to $n_1 = 1$ gives line of minimum wavelength.

$$\frac{1}{\lambda_{min}} = R\left[\frac{1}{1^2} - \frac{1}{\infty^2}\right] = 1.1\times10^7$$

$$\therefore \lambda_{min} = 912Å$$

(ii) Lyman series lies in ultraviolet region of electro magnetic spectrum

(iii) Lyman series is obtained in emission as well as in absorption spectrum.

(b) Balmer Series : Lines corresponding to $n_2 = 3, 4, 5, ...\infty$ to $n_1 = 2$ constitute Balmer series. The wave numbers of different lines are given by,

$$\bar{v} = \frac{1}{\lambda} = R\left[\frac{1}{2^2} - \frac{1}{n_2^2}\right]$$

(i) Line corresponding to transition $n_2=3$ to $n_1=2$ is first line, wavelength corresponding to this transition is maximum. Line corresponding to transition $n_2 = \infty$ to $n_1 = 2$ is last line; wavelength of last line is minimum.

$$\frac{1}{\lambda_{max}} = R\left[\frac{1}{2^2} - \frac{1}{3^2}\right]$$

$$\therefore \lambda_{max} = 6568Å$$

$$\frac{1}{\lambda_{min}} = R\left[\frac{1}{2^2} - \frac{1}{\infty^2}\right]$$

$$\therefore \lambda_{min} = 3636Å$$

(ii) Balmer series lies in the visible region of electromagnetic spectrum. The wavelength of L_α line is 656.8 nm (red). The wavelength of L_β line is 486 nm (blue green). The wavelength of L_γ line is 434 nm (violet). The remaining lines of Balmer series closest to violet light wavelength. The speciality of these lines is that in going from one end to other, the brightness and the separation between them decreases regularly.

(iii) This series is obtained only in emission spectrum. Absorption lines corresponding to Balmer series do not exist, except extremely weakly, because very few electrons are normally in the state n = 2 and only a very few atoms are capable of having an electron knocked from the state n = 2 to higher states. Hence photons that correspond to these energies will not be strongly absorbed. In highly excited hydrogen gas there is possibility for detecting absorption at Balmer-line wavelengths.

(c) Paschen Series :

Lines corresponding to $n_2 = 4,5,6,.......\ \infty$ to $n_1 = 3$ constitute Paschen series. The wave number of different lines are given by $\bar{v} = R\left[\frac{1}{3^2} - \frac{1}{n_2^2}\right]$

(i) Line corresponding to transition $n_2 = 4$ to $n_1 = 3$ is first line, having maximum wavelength. Line corresponding to transition $n_2 = \infty$ to $n_1 = 3$ is last line, having minimum wavelength

$$\frac{1}{\lambda_{max}} = R\left[\frac{1}{3^2} - \frac{1}{4^2}\right] \quad \therefore \lambda_{max} = 18747 Å$$

$$\frac{1}{\lambda_{min}} = R\left[\frac{1}{3^2} - \frac{1}{\infty}\right] = 1.1\times10^7 \times \left[\frac{1}{9} - 0\right]$$

$$\therefore \lambda_{min} = 8202 Å$$

(ii) Paschen series lies in the infrared region of electromagnetic spectrum.

(iii) This series is obtained only in the emission spectrum.

(d) Bracket Series :

The series corresponds to transitions from $n_2 = 5,6,7....... \infty$, to $n_1 = 4$. The wave number are given by,

$$\bar{v} = \frac{1}{\lambda} = R\left[\frac{1}{4^2} - \frac{1}{n_2^2}\right]$$

(i) Line corresponding to transition from $n_2 = 5$ to $n_1 = 4$ has maximum wavelength and $n_2 = \infty$ to $n_1 = 4$ has minimum wavelength.

$$\frac{1}{\lambda_{max}} = R\left[\frac{1}{4^2} - \frac{1}{5^2}\right] \therefore \lambda_{max} = 40477 Å$$

$$\frac{1}{\lambda_{min}} = R\left[\frac{1}{4^2} - \frac{1}{\infty^2}\right] \therefore \lambda_{min} = 14572 Å$$

(ii) This series lies in the infrared region of electromagnetic spectrum.

(e) Pfund Series :

This series corresponds to transitions from $n_2 = 6,7,8,....,\infty$ *to* $n_1 = 5$. The wave numbers are given by

$$\bar{v} = \frac{1}{\lambda} = R\left[\frac{1}{5^2} - \frac{1}{n_2^2}\right]$$

(i) Line corresponding to transition from $n_2 = 6$ to $n_1 = 5$ has maximum wavelength and $n_2 = \infty$ to $n_1 = 4$ has minimum wavelength.

$$\frac{1}{\lambda_{max}} = R\left[\frac{1}{5^2} - \frac{1}{6^2}\right]$$

$$\therefore \lambda_{max} = 74563 Å \quad \frac{1}{\lambda_{min}} = R\left[\frac{1}{5^2} - \frac{1}{\infty^2}\right]$$

$$\therefore \lambda_{min} = 22768 Å$$

(ii) This series lies in infrared region of electromagnetic spectrum.

V. Composition of the nucleus : Central part of the atom is called nucleus. It was first discovered by **Rutherford.**

1. The nucleus is spherical in shape and has a diameter of the order of 10^{-14} m.
2. The atomic nucleus is composed of elementary particles called protons and neutrons.

3. Protons has positive charge whose magnitude is equal to the charge of an electron but heavier than electron.
4. The neutron is electrically neutral and has a mass slightly greater than that of a proton.
5. Protons and neutrons are the building blocks of nucleus and are collectively called nucleons.
6. The number of protons in the nucleus is equal to the atomic number denoted by "Z". The number of neutrons is denoted by "N". The total number of neutrons and protons (nucleons) in the nucleus is called mass number (A) of the atom or nucleus i.e., A=Z+N.
7. A nucleus is symbolically represented by $_ZX^A$ in which X is the chemical symbol of the element. Eg. $_7N^{14}$ represents the nitrogen nucleus which contain 14 nucleons (7 protons and 7 neutrons)
8. Nuclides with same number of protons but different numbers of neutrons i.e. same atomic number Z, different neutron number N and different mass number A, are called isotopes.
9. Isotopes occupy same position in the periodic table and hence, they possess identical chemical properties and possess different nuclear properties.
10. $_1^1H$, $_1^2H$, $_1^3H$ are the isotopes of hydrogen atom.
11. $_8^{16}O$, $_8^{17}O$, $_8^{18}O$ are the isotopes of oxygen atom.
12. Nuclides with same number of neutrons N, but with different atomic number Z, and different mass number A are called isotones.
    $_7^{17}N$, $_8^{18}O$, $_9^{19}F$ are isotones.
13. Nuclides with same total number of nucleons A but differ in atomic number Z and also differ in neutron number N are called isobars.
    $_6^{14}C$, $_7^{14}N$ are isobars.
14. Nuclides having equal mass number A and atomic number Z but differing from one another in their nuclear energy states are called isomers.
15. $_{38}^{87}Sr^m$ is an isomer of $_{38}^{87}Sr^g$, where m denotes metastable state and g denotes ground state.
16. Nuclides having the same mass number A but with number of protons and neutrons interchanged are known as mirror nuclei $_4^7Be$ and $_3^7Li$.
17. **Nuclear size :** The distance of closest approach of α-particle to the nucleus was taken as a measure of nuclear radius which is approximately 10^{-15} m. The volume of the nucleus v is proportional to its mass number. If R is the radius of the nucleus then $R=R_0A^{1/3}$.
    where R_0 is constant its value is $1.1x10^{-15}$ m.
18. Nuclear distances are measured in units of fermi and 1 fermi=10^{-15} m.
19. The density of the nucleus is independent of mass number i.e. the density of nuclei of all atoms is same and is equal to $2.97x10^{17}$ kg m^{-3}.
20. The density of the nucleus is maximum at the centre and fall to zero, as we move rapidly outwards.
21. The nucleus does not have sharp boundaries.
22. The effective value of the radius of the nucleus is taken as the distance between its centre to the point where the density falls to half of its value at the centre.
23. **a.m.u :** The magnitude of the masses of the building blocks of an atom is expressed in atomic mass unit. It is defined as one twelfth of the mass of the carbon-12 atom.
    1 a.m.u=$1.66054021x10^{-27}$ kg
    The energy equivalent of 1 amu=931.54 MeV.

24. Nuclear Force : It is the force of attraction between a proton and proton, proton and neutron and between a neutron and another neutron. It is a strong force. The relative strengths of gravitational, Coulomb's and nuclear forces among the nucleons are in the ratio $F_g:F_c:F_n=1:10^{36}:10^{38}$.