STRUCTURE OF ATOM AND NUCLEI

Chap-15

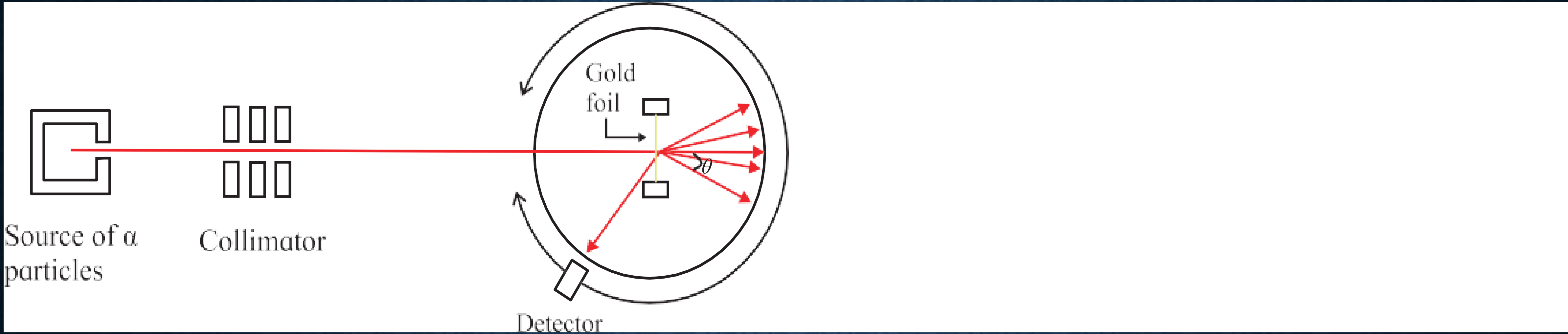
DALTON THEORY FOR STRUCTURE OF ATOM

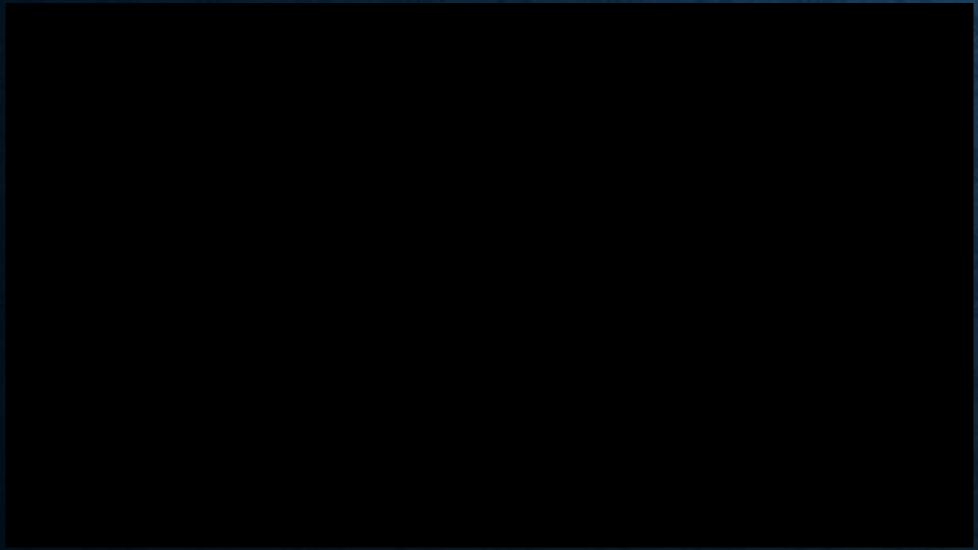
- According to his theory (i) matter is made up of indestructible particles, (ii) atoms of a given element are identical and (iii) atoms can combine with other atoms to form new substances
- It can also be stated as, atom is tiny, hard and indivisible particle of matter.

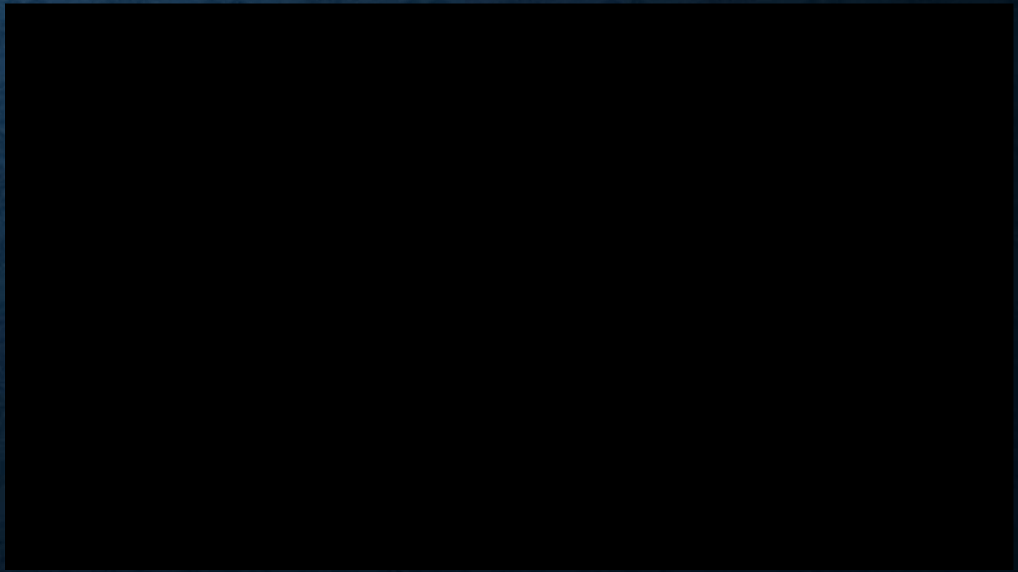
THOMSON'S ATOMIC MODEL

- Thomson performed several experiments with glass vacuum tube wherein a voltage was applied between two electrodes inside an evacuated tube
- The cathode was seen to emit rays which produced a glow when they struck the glass behind the anode
- By studying the properties of these rays, he concluded that the rays are made up of negatively charged particles which he called electrons
- This demonstrated that atoms are not indestructible
- Thomson proposed his model of an atom in 1903. According to this model an atom is a sphere having a uniform positive charge in which electrons are embedded
- This model is referred to as Plum-pudding model
- The total positive charge is equal to the total negative charge of electrons in the atom, rendering it electrically neutral
- As per this model, the whole solid sphere is uniformly positively charged, the positive charge cannot come out and only the negatively charged electrons which are small, can be emitted

GEIGER-MARSDEN EXPERIMENT







OBSERVATION

- https://phet.colorado.edu/sims/html/rutherford-scattering/latest/rutherford-scattering_en.html

CONCLUSION OF EXPERIMENT BY RUTHERFORD

- As almost all of the incident alpha particles would get deflected only through very small angles, the volume density of the positive charge would thus be very small.
- the alpha particles which were deflected back must have encountered a massive particle with large positive charge so that it was repelled back
- From the fact that extremely small number of alpha particles turned back while most others passed through almost undeflected, he concluded that the positively charged particle in the atom must be very small in size and must contain most of the mass of the atom.
- From the experimental data, the size of this particle was found to be about 10 fm (femtometre, 10-15) which is about 10-5 times the size of the atom
- most alpha particles pass through this without deflected, because of large empty space in the atom.
- very few which are in direct line with the tiny nucleus or are extremely close to it, get repelled and get deflected through large angles

RUTHERFORD'S ATOMIC MODEL

- He proposed that the entire positive charge and most (99.9%) of the mass of an atom and total positive charge are concentrated in the central nucleus and the electrons revolve around it in circular orbits, similar to the revolution of the planets around the Sun in the Solar system
- The revolution of the electrons was necessary as without it, the electrons would fall into the positively charged nucleus and the atom would collapse
- The space between the orbits of the electrons and the nucleus is mostly empty

DIFFICULTIES WITH RUTHERFORD'S MODEL

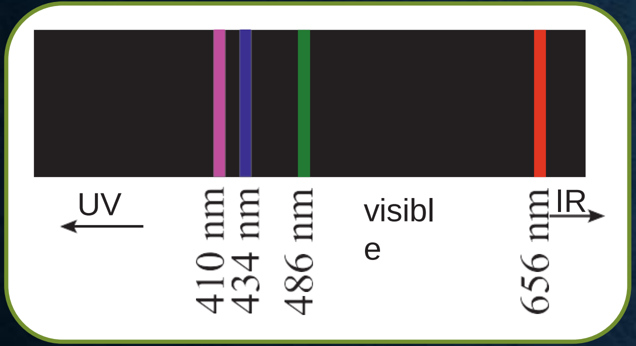
1) As per Rutherford atomic model, an electron in Rutherford's model moves uniformly along a circular orbit around the nucleus.

- Even though the magnitude of its velocity is constant, its direction changes continuously and so the motion is an accelerated motion
- Thus, the electron should emit electromagnetic radiation continuously, but this is not observed.

2) If electron will emits radiation, its energy would decrease and consequently, the radius of its orbit would decrease continuously.

- It would then spiral into the nucleus, causing the atom to collapse and lose its atomic properties, but its not observed too.

ATOMIC SPECTRA



- when a metallic object is heated, it emits radiation of different wavelengths
- When this radiation is passed through a prism, we get a continuous spectrum
- However, the case is different when we heat hydrogen gas inside a glass tube to high temperatures
- The emitted radiation has only a few selected wavelengths and when passed through a prism we get what is called a line spectrum
- It shows that hydrogen emits radiations of wavelengths 410, 434, 486 and 656 nm and does not emit any radiation with wavelengths in between these wavelengths.
- The lines seen in the spectrum are called emission lines
- Hydrogen atom also emits radiation at some other values of wavelengths in the ultraviolet (UV), the infrared (IR) and at longer wavelengths
- The spectral lines can be divided into groups known as series with names of the scientists who studied them
- The series, starting from shorter wavelengths and going to larger wavelengths are called Lyman series, Balmer series, Paschen series, Brackett series, Pfund series, etc.
- The observed wavelengths of the emission lines are found to obey the relation given by, $\frac{1}{\lambda} = \mathrm{R}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$
- Here λ is the wavelength of a line, R is amconstant and n and m are integers

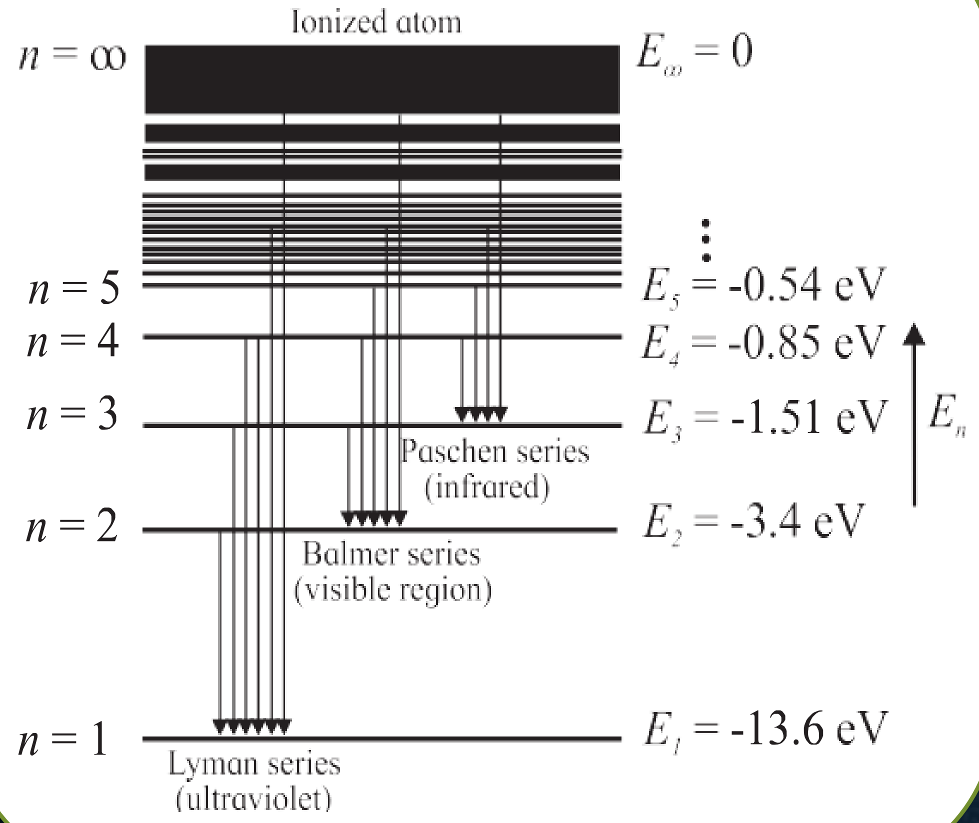
BOHR'S ATOMIC MODEL

- He made three postulates which defined his atomic model for stability of the orbits.
- **Bohr's fist postulate:** Electron revolve in circular orbit around the nucleus, the necessary centripetal force provided by electrostatic force of attraction between positive charge nucleus and negative charge electron
- Since centripetal force $F_c = \frac{m\,V^2}{r_n}$, and Electrostatic force is $F_E = \frac{1}{4\Pi\varepsilon_0}\frac{Ze^2}{r_n^2}$
- Hence, for stable atom, $F_c = F_E$ i.e. $\frac{m\,V^2}{r_n} = \frac{1}{4\Pi\varepsilon_0}\frac{Ze^2}{r_n^2}$
- **Bohr's fist postulate:** Electron revolve only in those orbit for which angular momentum of moving electron is equal to integral multiple of h/2Π, where h is Planck's constant.
- Since angular momentum of electron in respective orbit is, $L_n = mv_n r_n$ and as per postulate L_n= nh/2Π
- Hence, $mv_n r_n$= nh/2Π
- **Bohr's fist postulate:** When electron jumps from higher orbits to lower orbit, it emits energy in the form of quanta (Photon), the energy of photon is energy difference between both the orbits.
- Since energy of photon is, E_{ph} = hυ and as per postulate energy of photon is $E_{ph} = E_m - E_n$, where E_n is energy of higher orbit and E_m is energy of lower orbit.
- Hence, hυ = $E_n - E_m$

ENERGY OF THE ELECTRONS

- Since, as per first postulate of Bohr's, $\frac{m V^2}{r_n} = \frac{1}{4\Pi\varepsilon_0} \frac{Ze^2}{r_n^2}$

ENERGY LEVEL DIAGRAM FOR HYDROGEN ATOM



RYDBERG'S FORMULA OR EMPIRICAL FORMULA

- According to the third postulate of Bohr, when an electron makes a transition from p^{th} to n^{th} orbit ($p > n$), the excess energy *Ep* - *En* is emitted in the form of a photon.
- The energy of the photon which can be written as $h\nu$, ν being its frequency, is therefore given by h ν= *Ep* – *En*
- *But Ep*$= -\frac{mZ^2e^4}{8\varepsilon_0^2p^2}$ *and En*$= -\frac{mZ^2e^4}{8\varepsilon_0^2n^2}$
- *By using Bohr's third postulate,* h ν= *Ep* – *En* $= -\frac{mZ^2e^4}{8\varepsilon_0^2h^2p^2}$ - $\left(-\frac{mZ^2e^4}{8\varepsilon_0^2n^2}\right)$

$$= \frac{mZ^2e^4}{8\varepsilon_0^2h^2}\left(\frac{1}{n^2} - \frac{1}{p^2}\right)$$

$$=> h\,\frac{c}{\lambda} = \frac{mZ^2e^4}{8\varepsilon_0^2h^2}\left(\frac{1}{n^2} - \frac{1}{p^2}\right)$$

$$=> \frac{1}{\lambda} = \frac{mZ^2e^4}{8\varepsilon_0^2ch^3}\left(\frac{1}{n^2} - \frac{1}{p^2}\right) = R\,Z^2\left(\frac{1}{n^2} - \frac{1}{p^2}\right)$$

where $R = \frac{mZ^2e^4}{8\varepsilon_0^2ch^3}$ *is Rydberg's constant, the value is 1.0973*$\times 10^7$ *per meter*

- *For hydrogen atom(z=1),* $\frac{1}{\lambda} = R\left(\frac{1}{n^2} - \frac{1}{p^2}\right)$

LIMITATIONS OF BOHR'S MODEL

- It could not explain the line spectra of atoms other than hydrogen. Even for hydrogen, more accurate study of the observed spectra showed multiple components in some lines which could not be explained on the basis of this model.
- The intensities of the emission lines seemed to differ from line to line and Bohr's model had no explanation for that
- On theoretical side also the model was not entirely satisfactory as it arbitrarily assumed orbits following a particular condition to be stable. There was no theoretical basis for that assumption

DE BROGLIE'S EXPLANATION FOR BOHR'S SECOND POSTULATE

- De Broglie suggested that instead of considering the orbiting electrons inside atoms as particles, we should view them as standing waves Or wave associated with electron is standing wave.
- For stationery wave, only those wave survive, for which the path length, is integral multiple of λ.
- Since path length of moving electron is = circumference of circle = $2\pi r_n$
- Thus $2\pi r_n$= n λ
- As per de Broglie hypothesis, $\lambda = \frac{h}{p} = \frac{h}{mV_n}$
- Hence, $2\pi r_n = \frac{nh}{mV_n}$
- => $mV_n r_n = \frac{nh}{2\pi}$
- => L_n= n $\frac{h}{2\pi}$

CONSTITUENTS OF A NUCLEUS

- ***Nucleons:*** The atomic nucleus is made up of subatomic, meaning smaller than an atom, particles called ***protons*** and ***neutrons***. Together, protons and neutrons are referred to as ***nucleons.***
- Mass of a proton is about 1836 times that of an electron
- Mass of a neutron is nearly same as that of a proton but is slightly higher
- The neutron, as the name suggests, is electrically neutral
- ***Atomic number :*** The number of protons in an atom is called its ***atomic number*** and is designated by ***Z***
- The number of neutrons in a nucleus is written as ***N***
- ***Mass number :*** The total number of nucleons in a nucleus is called the ***mass number*** of the atom and is designated by ***A*** = Z + N
- The mass number determines the mass of a nucleus and of the atom
- The atoms of an element X are represented by the symbol for the element and its atomic and mass numbers as $^{A}_{Z}X$
- ***Isotopes:*** Atoms having the same number of protons but different number of neutrons are called ***isotopes.***
- deuterium and tritium are isotopes of hydrogen
- ***Isobars:*** The atoms having the same mass number A, are called ***isobars***
- Ex. Thus, 3 H and 3 He are isobars
- ***Isotones:*** Atoms having the same number of neutrons but different values of atomic number Z, are called ***iosotones.***

UNITS FOR MEASURING MASSES OF ATOMS AND SUBATOMIC PARTICLES

- Obviously, kg is not a convenient unit to measure masses of atoms or subatomic particles which are extremely small compared to one kg
- Therefore, another unit called the unified atomic mass unit (u) is used for the purpose
- One u is equal to 1/12th of the mass of a neutral carbon atom having atomic number 12, in its lowest electronic state.
- 1 u = 1.6605402 × 10-27 kg

LAW OF RADIOACTIVE DECAY

- Statement: Number nuclei of radio active material undergoing decay per unit time is directly proportional to number of unchanged nuclei present at that instant of time.
- Let us assume that at time t, number of parent nuclei which are left is *N, and* number of nuclei decays *dN* in time interval *dt.*
- *As per law of radio active decay* $-\frac{dN}{dt} \alpha N$

$$\frac{dN}{dt} = -\lambda N$$ where, λ is a constant of proportionality called the ***decay constant***

- ***Let*** at time t=0, the number unchanged nuclei N_0, and after time = t, the number of unchanged nuclei is *N(t), that can be found as follows, dN*= -$\lambda N\, dt$ => $\int_{N_0}^{N} dN = \int_0^t -\lambda N\, dt$

$$\int_{N_0}^{N} \frac{1}{N} dN = -\lambda \int_0^t dt$$

$$[\ln N]_{N_0}^{N} = -\lambda t \Rightarrow \ln N - \ln N_0 = -\lambda t$$

$$\ln\left[\frac{N}{N_0}\right] = -\lambda t \Rightarrow \frac{N}{N_0} = e^{-\lambda t} \Rightarrow N = N_0\, e^{-\lambda t}$$

- $-\frac{dN}{dt}$ is also called Activity A(t),
- Activity is measured in units of becquerel (Bq) in SI units, One becquerel is equal to one decay per second.
- Another unit to measure activity is curie (Ci). One curie is 3.7 x 10^{10} decays per second. Thus, 1 Ci = 3.7 x 10^{10} Bq

CALCULATE THE BINDING ENERGY OF AN ALPHA PARTICLE GIVEN ITS MASS TO BE 4.00151 U.

- Mass of proton (mp) = 1.00728u
- Mass of neutron (mn)= 1.00866u
- (take u= 939.565 MeV/c2)
- The alpha particle has two proton and two neutron.
- The combined mass of nuclei = net mass of proton + net mass of neutron
- $=(2\times1.00728)+(2\times1.00866)$
- =4.03188 amu
- Binding energy =mass defect
- $=4.03188-4.00151$
- $=0.03037\times u$
- =0.03037(939.565)
- =28.53 MeV

AN ELECTRON IN HYDROGEN ATOM STAYS IN ITS SECOND ORBIT FOR 10-8 S. HOW MANY REVOLUTIONS WILL IT MAKE AROUND THE NUCLEUS IN THAT TIME?

Data: z = 1, m = 9.1 x 10^{-31} kg, e = 1.6 x 10^{-19} C, ε_0 = 8.85 x 10^{-12} $C^2/N \cdot m^2$, h = 6.63 x 10^{-34} J.s, n = 2, t = 10^{-8} s

The periodic time of the electron in a hydrogen atom,

$$T = \frac{4\varepsilon_0^2 h^3 n^3}{\pi m e^4}$$

$$= \frac{(4)\left(8.85 \times 10^{-12}\right)^2 \left(6.63 \times 10^{-34}\right)^3 (8)}{(3.142)\left(9.1 \times 10^{-31}\right)\left(1.6 \times 10^{-19}\right)^4}$$

$$= \frac{(4)(8.85)^2(6.63)^3(8)}{(3.142)(9.1)(1.6)^4} \times 10^{-19} \text{s}$$

$$= 3.898 \times 10^{-16} \text{ s}$$

Let N be the number of revolutions made by the electron in time t. Then, t =NT.

$$\therefore N = \frac{t}{T} = \frac{10^{-8}}{3.898 \times 10^{-16}} = 2.565 \times 10^7$$