Revision Notes

Class 12 Physics

Chapter 12 - Modern Physics (Atoms)

1. NUCLEUS

1.1 Isotopes

The atoms of an element, which constitute the same atomic number but different mass numbers are termed isotopes. Some examples are:

(i) $_8O^{16}, _8O^{17}, _8O^{18}$

(ii) $_{17}O^{35}, _{17}Cl^{37}$

(iii) $_{82}Pb^{206}, _{82}Pb^{207}, _{82}Pb^{208}$.

1.2 Isotones

The atoms whose nuclei constitute the same number of neutrons are termed isotones.

1.3 Isobars

The atoms which constitute the same mass numbers but different atomic numbers are termed isobars. Some examples are:

(i) $_1H^3$ and $_1He^3$

(ii) $_2Li^7$ and $_4Be^7$

(iii) $_{28}Ar^{40}$ and $_{29}Ca^{40}$

(iv) Ge^{76} and $_{34}Se^{76}$

1.4 Atomic mass unit

Atomic mass unit (a.m.u) refers to a very small unit of mass and it is observed to be very convenient in nuclear physics.

It is defined as 1/12th the mass of one $_6C^{12}$ atom.

With respect to Avogadro's hypothesis, number of atoms in 12 g of $_6C^{12}$ is taken equivalent to the Avogadro number i.e., 6.023×10^{23}.

Thus, the mass of one carbon atom $(_6C^{12})$ is given by

$$\frac{12}{6.023\times10^{23}} = 1.992678\times10^{-26}\text{kg}$$

Further,

$$1\text{ amu} = \frac{1}{12}\times 1.992678\times 10^{-26}\text{kg}$$

$$\Rightarrow 1\text{ amu} = 1.660565\ \times\ 10^{-27}\text{kg}$$

1.5 Energy equivalent of atomic mass unit

With respect to the Einstein's mass-energy equivalence formula, the energy equivalent of mass m is expressed as $E = mc^2$, where c is the speed of light. If it is supposed that $m = 1\text{ amu} = 1.660565\times 10^{-27}\text{kg}$; and as $c = 2.998\times 10^8\text{ms}^{-1}$; the energy equivalent of 1 amu is given by

$$1\text{ amu} = \left(1.660565\times 10^{-27}\text{kg}\right)\times\left(2.998\times 10^8\text{ms}^1\right)^2 = 1.4925\times 10^{-10}\text{J}$$

Now, it is known that 1 MeV = 1.602×10^{-13}J;

Thus,

$$\Rightarrow 1\text{ amu} = \frac{1.4925\times 10^{-10}}{1.602\times 10^{-13}}\text{eV} = 931.5\text{ MeV}$$

1.6 Nuclear size

The volume of a nucleus is in direct proportion to the number of nucleons (mass number) involved in the nucleus. When R is the radius of the nucleus having mass number A, then,

$$\frac{4}{3}\pi R^3 \propto A \Rightarrow R \propto A^{\frac{1}{3}} \Rightarrow R = R_0 A^{\frac{1}{3}}$$

1.7 Nuclear density

Mass of the nucleus of the atom of mass number A is given by $A = A\text{ amu} = A\times 1.660565\times 10^{27}\text{kg}$

When R is radius of the nucleus, then,

$$\text{Volume of nucleus} = \frac{4}{3}R^3 = \frac{4}{3}\pi(R_0A^{1/3})^3 = \frac{4}{3}R^3{}_0A$$

Taking $R_0 = 1.1\times 10^{-15}\text{m}$;

Density of the nucleus is given by

$$\rho = \frac{\text{mass of nucleus}}{\text{volume of nucleus}} = \frac{A\times 1.66065\times 10^{-27}}{4/3\pi\left(1.1\times 10^{-15}\right)^3\times A} = 2.97\times 10^{17}\text{kgm}^{-3}$$

Clearly, density is independent of A.

Discussion:

- The densities of the nuclei of all atoms are equal as they are independent of the mass numbers.

- A high-density nucleus of an atom $\left(\approx 10^{17}\,\text{kgm}^{-3}\right)$ refers to the compactness of the nucleus. Such examples of high density nuclei are observed in the form of neutron stars.

1.8 Mass defect

The difference between the sum of the masses of the nucleons forming a nucleus and the rest mass of the nucleus is termed mass defect. It is represented by Δm.

Let us evaluate the mass defect for the nucleus of an atom ${}_z X^A$.

The nucleus of the atom consists of Z protons and $(A-Z)$ neutrons.

Thus, if m_N is the mass of the nucleus of the atom ${}_Z X^A$, then the mass defect is expressed as

$$m = \left[Zm_p + (A-Z)m_n m_N({}_Z X^A) \right]$$

The binding energy of a nucleus refers to the energy equivalent to the mass defect of the nucleus. It may be computed as the work required to be done to separate the nucleon to an infinite distance apart in order to make them no longer in contact with each other.

If Δm refers to mass defect of a nucleus, then according to Einstein's mass-energy relation, the binding energy of the nucleus is given by Δmc^2 (in joules).

Here, mass defect Δm has to be taken in kilograms. On the other hand, if the mass defect is taken in amu, then,

Binding energy of the nucleus $= \Delta m \times 931.5 (\text{in MeV})$

$$\Rightarrow \text{Binding energy } = \left[Zm_p + (A-Z)m_n - m_N({}_Z X^A) \right] \times 931.5$$

1.9 Binding Energy Per Nucleon

The binding energy per nucleon refers to the average energy required to extract a single nucleon from the nucleus. Clearly,

$$\text{binding energy per nucleon } = \frac{\text{binding energy}}{A}.$$

1.10 Packing Fraction

$$\text{Mathematically, packing fraction } = \frac{\text{mass defect}}{A}.$$

1.11 Natural Radioactivity

The sudden transformation of an element into another with the emission of a particle / few particles or electromagnetic radiation is termed natural radioactivity.

1.11.1 Laws of Radioactivity Decay

Rutherford and Soddy learnt the phenomenon of radioactivity in detail and put forward the following laws, known as the laws of radioactive decay:

a) Radioactivity is a sudden phenomenon and one cannot predict when a particular atom in a given radioactive sample would undergo disintegration.

b) When a radioactive atom disintegrates, either an α-particle (nucleus of helium) or a β-particle (electron) gets emitted.

c) The emission of an α-particle by a radioactive-atom results in a daughter atom, whose atomic number is 2 units less than that of the parent atom.

$$_{Z}X^{A} \xrightarrow{\alpha-\text{decay}} {}_{Z-2}Y^{A-4}$$

d) The emission of a β-particle by a radioactive-atom results in a daughter atom, whose atomic number is 1 unit more than that of the parent atom. However, the mass number remains the same as that of the parent atom.

$$_{Z}X^{A} \xrightarrow{\beta-\text{decay}} {}_{Z+1}Y^{A}$$

e) The number of atoms disintegrating per second of a radioactive sample at any time is in direct proportion to the number of atoms present at that time. The rate of disintegration of the sample cannot be changed by altering the external factors such as pressure, temperature, etc. This is known as radioactive decay law.

With respect to radioactive decay law, the rate of disintegration at any time t is in direct proportion to the number of atoms present at time. Mathematically, $\frac{dN}{dt} \propto N \Rightarrow \frac{dN}{dt} = -\lambda N$

Where, the constant of proportionality λ is termed the decay constant of the radioactive sample. It is also referred to as disintegration constant or transformation constant. Its value is dependent upon the nature of the radioactive sample. Also, the negative sign in the expression mentions that the number of the atoms of the sample reduces with the passage of time.

Simplifying the expression further by integrating,

$$\Rightarrow \int \frac{dN}{N} = -\int \lambda dt$$

$$\Rightarrow \log_e \frac{N}{N_0} = -\lambda t$$

$$\Rightarrow \frac{N}{N_0} = e^{-\lambda t}$$

$$\Rightarrow N = N_0 e^{-\lambda t} \Rightarrow N = N_0 e^{t}$$

1.11.2 Radioactive Decay Constant

From radioactive decay law,

$$\frac{dN}{dt} = -\lambda N$$

$$\Rightarrow \lambda = \frac{-dN/dt}{N}$$

Thus, radioactive decay constant of a substance (radioactive) refers to the ratio of its instantaneous rate of disintegration to the number of atoms present at that time.

Also do we have $N = N_0 e^{t}$.

Now, if $t = 1/\lambda$; then,

$$N = N_0 e^{-\lambda I/\lambda} = 1/e\ N_0 = N_0/(2.718) = 0.368\ N_0$$

Clearly, radioactive decay constant of a substance may also refer to the reciprocal of the time, after which the number of atoms of a radioactive substance reduces to 0.368 (or 36.8%) of their number present initially.

1.11.3 Half Life

Let a radioactive sample contain N_0 atoms at time $t = 0$.

The number of atoms left behind after time t is represented as $N = N_0 e^{t}$.

Using the definition of half life, it follows that when $t = t_{1/2}; N = N_0/2$.

Considering the above condition, it follows that

$$\Rightarrow \frac{N_0}{2} = N_0 e^{-\lambda t_{1/2}} = 2$$

$$\Rightarrow e^{-\lambda t_{1/2}} = \frac{1}{2} \Rightarrow e^{-\lambda t_{1/2}} = 2$$

$$\Rightarrow \lambda T = \log_e 2 = 2.303 \log_{10} 2 = 2.303 \times 0.3010 = 0.693$$

$$\Rightarrow t_{1/2} = \frac{0.693}{\lambda}$$

Clearly, half life of a radioactive substance is inversely proportional to its decay constant and can be considered as a characteristic property of its nucleus. It cannot be changed by any known method.

1.11.4 Mean life or average life

The average life of a radioactive substance refers to the average time for which the nuclei of the atoms of the radioactive substance exist. It is mathematically given by

$$t_{avg} = \frac{1}{\lambda}$$

1.11.5 Activity of radioactive substance

The activity of a radioactive substance refers to the rate at which the nuclei of its atoms in the sample disintegrate. When a radioactive sample consists of N atoms at any time t, then its activity at time t is given by

$$A = -\frac{dN}{dt}$$

The negative sign mentions that with the passage of time, the activity of the radioactive substance reduces.

Involving radioactive decay law, $\frac{dN}{dt} = -\lambda N$ and $N = N_0 e^{-\lambda t}$ here,

$$\Rightarrow A = \lambda N$$
$$\Rightarrow A = \lambda N_0 e^{-\lambda t}$$
$$\Rightarrow A = A_0 e^{-\lambda t}$$

Here, $\lambda N_0 = A_0$ is known as the activity of the radioactive sample at time $t = 0$.

1.11.6 Units of activity

The activity of a radioactive sample can be expressed as the number of disintegrations per second. The practical unit of activity of a radioactive sample is curie (Ci).

The activity of a radioactive sample is known to be one curie when it undergoes 3.7×10^{10} disintegrations per second.

Clearly, $1\ \text{curie(Ci)} = 3.7 \times 10^{10}\ \text{disintegrations / s}$

There is also another unit of radioactivity termed rutherford (Rd). The activity of a radioactive sample is known to be one rutherford when it undergoes 10^6 disintegrations per second.

Clearly, $1\ \text{rutherford}\ (\text{Rd}) = 10^6\ \text{disintegrations / s}$

1.12 Nuclear fission

The process of splitting of a heavy nucleus into two nuclei of nearly comparable masses with liberation of energy is termed nuclear fission. For example,

$$_{92}U^{235}+{}_{0}n^{1}\rightarrow\left[{}_{92}U^{236}\right]\rightarrow{}_{56}Ba^{141}+{}_{30}Kr^{92}+3{}_{0}n^{1}+Q$$

Neutron reproduction factor refers to the ratio of the rate of production of neutrons to the rate of loss of neutrons. Mathematically, it is given by,

$$k=\frac{\text{rate of production of neutrons}}{\text{rate of loss of neutrons}}$$

When $k=1$, fission reaction would be steady;

When $k>1$, the fission reaction would accelerate;

When $k<1$, the fission reaction would decelerate.

1.12.1 Nuclear Reactor

Main sections and their functions of a nuclear reactor are as follows:

1. Fuel: It is a fissionable material, generally U^{235}.
2. Moderator: It is used to reduce the speed of the neutrons released during the fission. The most popular moderators are water, heavy water and graphite.
3. Control Rods: These rods are made of cadmium or boron, that can control the chain reaction by absorbing neutrons.
4. Coolant and Heat Exchange: The coolant helps in taking away heat from the reactor core and thus heats the water in the heat exchanger to generate steam. The popularly used coolants are liquid sodium and heavy water.
5. Radiation Shielding: These are thick concrete walls that can stop the radiations from emitting out.

1.12.2 Radiation Hazards

1. The exposure to radiation induces harmful genetic effects.
2. The strong α -ray exposure has the potential to cause lung cancer.
3. The exposure to fast and slow neutrons may result in blindness.
4. The exposure to neutrons, protons and α -particles may result in damage to red blood cells.
5. The exposure to α-particles may also result in disastrous effects.
6. The strong exposure to protons and neutrons has the potential to cause serious damage to productive organs.

1.12.3 Safety Measures from Radiation Hazards

Precautions followed by the workers engaged in this field:

1. The radioisotopes are moved in thick-walled lead containers and are kept in rooms with thick walls of leads.
2. The radioisotopes are used with the help of remote-control devices.
3. The workers are suggested to wear lead aprons.
4. The radioactive contamination of the work area is taken care of at all costs.

2. CATHODE RAYS

When a potential difference of $10\text{-}15\,\text{kV}$ gets applied across the two electrodes of a discharge tube and when the pressure is reduced to 0.01mm of mercury, the rays termed as cathode rays are emitted from the cathode.
These rays are not dependent on the nature of the gas in the discharge tube and their direction of travel is unaffected by the position of the anode.

Properties of Cathode Rays:

1. Cathode rays propagate along straight lines and produce sharp shadows of the objects placed in their path.
2. Cathode rays are ejected normally from the surface of the cathode.
3. The direction of the cathode rays does not get affected by the position of the anode.
4. The cathode rays apply mechanical pressure.
5. The cathode rays generate heat when they fall upon matter.
6. The cathode rays get deflected with the presence of electric and magnetic fields.
7. When cathode rays encounter a solid target of high atomic weight such as tungsten, they generate a highly penetrating radiation called the X -rays.
8. Cathode rays ionize the gas through which they travel.
9. Cathode rays accelerate fluorescence.
10. Cathode rays can cause chemical changes.
11. Cathode rays can penetrate through thin sheets of matter without damaging them.
12. Cathode rays are observed to have velocities up to one tenth of the velocity of light.

3. FREE ELECTRONS IN METALS

Electrons can be considered as the fundamental constituent of an atom. A metal has free electrons that move about freely through the atomic spaces randomly. However, as soon as an electron leaves the metal, an equal positive charge gets produced on the surface of the metal. As a consequence, the electron is pulled back into the metal and thus remains contained in it. The pull on the electrons at the surface is observed to be dependent on the nature of the metal surface and is expressed by a characteristic of the metal termed work function.

Work Function

The minimum energy that should be supplied to the electron for it to just come out of a metal surface is termed the work function of that metal.

This process is known as electron emission and can be achieved in the following ways:

1. Thermionic emission: Here, the extra energy is supplied in the form of heat. The emitted electrons are called thermo-electrons.
2. Photoelectric emission: Here, the extra energy is supplied by means of electromagnetic radiation. The emitted electrons are called photoelectrons.
3. Secondary emission: Here, the fast-moving electrons on collision with the metal surface kicks out electrons, known as secondary electrons.
4. Field emission: Here, electrons are emitted with the help of electrostatic field.

4. PHOTOELECTRIC EFFECT

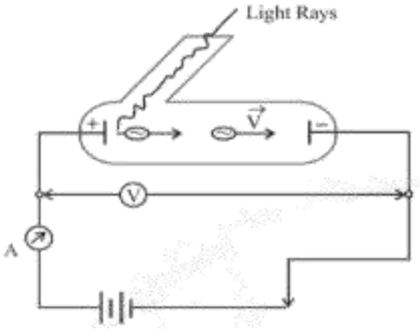
The phenomenon of ejecting electrons from a metal surface, when light of sufficiently high frequency encounters it is termed as photoelectric effect. The electrons ejected are called photoelectrons.

Experimental Study of Photoelectric Effect:

The setup consists of an evacuated glass tube joined with two electrodes. The electrode E is known as emitting electrode and the other electrode C is known as collecting electrode.

When a suitable radiation falls on the electrode E, electrons are emitted from it. The electrons, which have sufficient kinetic energy, travel to the electrode C, despite its negative polarity. The potential difference between the two electrodes forms the retarding potential. As the collecting electrode is made more and more negative, fewer and fewer electrons would reach the cathode and the photo-electric current measured by the ammeter would fall.

When the retarding potential is equal to V_0, known as the stopping potential, no electron would reach the cathode and the current would become zero. In such a case, the work done by stopping potential is the same as the maximum kinetic energy of the electrons. i.e., $eV_0 = 1/2\ mv^2_{max}$.



4.1 Laws of Photoelectric Emission

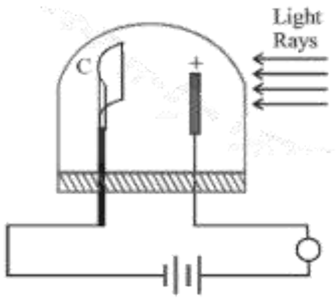
1. The emission of photoelectrons happens only when the frequency of the incident radiation is more than a certain critical value, which is a characteristic of that metal. The critical value of frequency is termed the threshold frequency for the metal of the emitting electrode.
2. The emission of photoelectrons begins as soon as light falls on metal surface.
3. The maximum kinetic energy with which an electron gets emitted from a metal surface is not dependent on the intensity of the light and is dependent only upon its frequency.
4. The number of photoelectrons emitted, i.e., photoelectric current, is not dependent on the frequency of the incident light and is dependent only upon its intensity.

4.2 Photoelectric Cell

A photoelectric cell is a setup which converts light energy into electrical energy. Photoelectric cells are of the following three types:

1. Photo emissive cells
2. Photovoltaic cells
3. Photoconductive cells

   A photo emissive cell may be of vacuum type or gas filled type.



Working - Photo emissive Cells:
It involves two electrodes, a cathode C and an anode A, contained in a highly evacuated glass bulb. The cathode C is a semi-cylindrical plate layered with a photosensitive material. This is known as de-Broglie relation of caesium deposited on silver oxide. The anode A is in the shape of a wire, so that it is not obstructing the path of the light incident on the cathode.
When light of frequency greater than the threshold frequency of the cathode surface falls on the cathode, photoelectrons get emitted. When a potential difference of about $10V$ is applied between the anode and cathode, the photoelectrons get attracted towards the anode and the micro ammeter connected in the circuit would record the current.

4.3 Applications of Photoelectric Cell:

1. It is utilized in a television studio for the conversion of the light and shade of the object into electric currents for transmission of pictures.
2. It is utilized in a photographic camera for the automatic adjustment of aperture.
3. It is utilized for automatic counting of the number of people entering a hall or a stadium.
4. It is utilized in automatic switching of street lights and traffic signals.
5. It is utilized for raising a fire alarm in case of emergencies like accidental fire in buildings, factories, etc.
6. It is utilized in burglar’s alarms for houses, banks and treasuries.

5. DUAL NATURE OF RADIATION

The different phenomena concerning radiation can be categorized into three parts:

1. In phenomena such as interference, diffraction, polarization, etc., the interaction of radiation takes place with the radiation itself. Such phenomena can be expressed on the basis of electromagnetic (wave) nature of radiation only.
2. In phenomena such as photoelectric effect, Compton effect, etc., interaction of radiation takes place with matter. Such phenomena can be expressed on the basis of quantum (particle) nature of radiation.
3. In phenomena such as rectilinear propagation, reflection, refraction, etc., neither the interaction of radiation takes place with radiation nor of radiation with matter. Such phenomena can be expressed on the basis of either of the two natures (wave or particle) of the radiation.

6. DE BROGLIE WAVES

Louis-Broglie presented a bold hypothesis that matter must also possess dual nature.

The following observations made him realise the duality hypothesis for matter.

1. The whole energy in this universe is in the form of matter and electromagnetic radiation.
2. Nature loves symmetry. As the radiation has dual nature, matter must also possess dual nature.

Clearly, according to de-Broglie's hypothesis, every moving particle has a wave associated with it. Such waves are called de-Broglie waves or matter waves. With respect to the quantum theory of radiation, energy of a photon is given by

$$E = h\nu \ldots (i)$$

Also, the energy of a relativistic particle is given by

$$E = \sqrt{m_0^2c^2 + p^2 + c}$$

As photon is a particle of zero rest mass, considering $m_0 = 0$ in the above equation, we have

$$E = pc \ldots (ii)$$

$$\Rightarrow pc = h\nu$$

$$\Rightarrow p = \frac{h\nu}{c} = \frac{h\nu}{\nu\lambda} (\because c = \nu\lambda)$$

$$\Rightarrow p = \frac{h}{\lambda}$$

Thus, the wave-length of the photon is given by

$$\Rightarrow \lambda = \frac{h}{p} \ldots (iii)$$

Clearly, de-Broglie wavelength is given by

$$\lambda = \frac{h}{mv} \ldots (iv)$$

This is known as the de-Broglie relation.

6.1 Conclusion

1. Lighter the particle, greater is its de-Broglie wavelength.
2. The faster the particle travels, the smaller is its de-Broglie wavelength.
3. The de-Broglie wavelength of α -particle is not dependent on the charge or nature of the particle.

4. The matter waves are not electromagnetic in nature. If the velocity of the particle is comparable to the velocity of light, then mass of the particle is given by

$$m = \frac{m_0}{\sqrt{1 - v^2 / c^2}}$$

6.2 De-Broglie Wavelength of Electron

Suppose that an electron of mass m and charge e is made to accelerate through a potential difference V. When E is the energy acquired by the particle, then, $E = eV \ldots (i)$

Now, if v is the velocity of electron, then

$$E = \frac{1}{2} mv^2 \Rightarrow v = \sqrt{\left(\frac{2E}{m}\right)}$$

Now, de-Broglie wavelength of electron is given by

$$\Rightarrow \lambda = \frac{h}{mv} = \frac{h}{m\sqrt{2E/m}} \ldots (iii)$$

Substituting the value of E,

$$\Rightarrow \lambda = \frac{h}{\sqrt{2meV}} \ldots (iv)$$

Considering $m = 9.1 \times 10^{-31}$ kg; $e = 1.6 \times 10^{-29}$ C and $h = 6.62 \times 10^{-34}$ Js,

$$\Rightarrow \lambda = \frac{12.27}{\sqrt{V}} \times 10^{-10} \mathrm{m}$$

$$\Rightarrow \lambda = \frac{12.27}{\sqrt{V}} \mathrm{A} \ldots (v)$$

For instance, the de-Broglie wavelength of electrons when accelerated through a potential difference of 100 volt would be

$$\lambda = \frac{12.27}{\sqrt{100}} \approx 1.227 \mathrm{A}$$

Clearly, the wavelength of de-Broglie wave associated with 100eV electrons is of the order of the wavelength of X-rays.

7. THOMSON'S ATOM MODEL

In this model, positive charges are uniformly distributed over the entire sphere and the electrons are contained in the sphere of these positive charges just like seeds in a watermelon or plums in the pudding. Due to this reason, Thomson's atom model is also called the plum-pudding model.

The total positive charge inside the atom is the same as the total negative charge carried by electrons, so that every atom is electrically neutral. When the atom gets slightly disturbed, the electrons in the atoms vibrate about their equilibrium position and result in the ejection of radiation of definite frequencies in the form of infra-red, visible or ultraviolet light.

Failure of Thomson's Atom Model

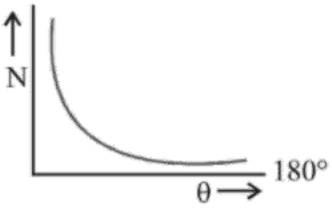
This model had to be discarded because of the following reasons:

1. It could not express the origin of the spectral lines in the form of series as in the case of hydrogen atoms.
2. It could not clearly express the scattering of α particles through large angles as in case of Rutherford's α scattering experiment.

8. RUTHERFORD'S ALPHA SCATTERING EXPERIMENT

Following are the observation made through this experiment:

1. Most of α -particles were seen to pass through the fold foil without any appreciable deflection.
2. The various α particles, on passing through the gold foil, undergo different amounts of deflections. A large number of α particles caused fairly large deflections.
3. A very small number of α -particles (about 1 in 8000) practically retracted their paths or suffered deflection of nearly 180° .
4. The plot between the total number of α - particles $N(\theta)$ scattered through angle θ and the scattering angle θ was found to be as shown in graph:



These experimental observations led Rutherford to the following inferences:

1. As most of the α particles passed without any deviation, the atom had a lot of empty space in it.
2. As fast and heavy α particles could be deflected even through 180°, the whole of the positive charge and practically the entire mass of the atom were confirmed to extremely small central cores. These were called nuclei. Because 1 in about 8000 α particles get deflected through 180°, the size of the nucleus was assumed to be about $1/10000\text{th}$ of the size of the atom.

8.1 Rutherford's Atom Model

On the basis of the results of α scattering experiment, Rutherford suggested the following picture of an atom:

1. Atoms can be regarded as spheres of diameters $10^{-10}\,m$ but whole of the positive charge and almost the entire mass of these atoms are concentrated in small central cores called nuclei having diameters of about $10^{-14}\,m$.
2. The nucleus is neighbored by electrons. In other words, the electrons are distributed over the remaining part of the atom leaving plenty of empty space in the atom.

8.2 Drawbacks of Rutherford's Atom Model

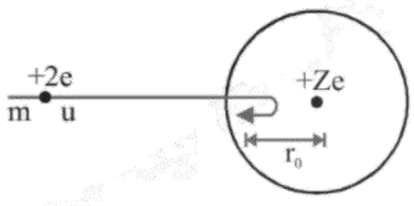
1. When the electrons revolve around the nucleus, they get continuously accelerated towards the center of the nucleus. According to Lorentz, an accelerated charged particle must radiate energy continuously. Thus, in the atom, a revolving electron must continuously emit energy and hence the radius of its path must go on decreasing and finally, it must fall into the nucleus. However, electrons revolve around the nucleus without falling into it. Clearly, Rutherford's atom model couldn't explain the stability of the atom.
2. Suppose if Rutherford's atom model is true, the electron could revolve in orbits of all possible radii and thus it should emit a continuous energy spectrum. But, atoms like hydrogen possess a line spectrum.

8.3 Distance of Closest Approach

Suppose an α a particle of mass m possesses an initial velocity u when it is at a large distance from the nucleus of an atom having atomic number Z. At the distance of closest approach, the kinetic energy of α particle gets completely converted into potential energy. Mathematically,

$$\frac{1}{2}mu^2 = \frac{1}{4\pi\varepsilon_0}\frac{(2e)(Ze)}{r_0}$$

$$\Rightarrow r_0 = \frac{1}{4\pi\varepsilon_0}\frac{2Ze^2}{\left(\frac{1}{2}mu^2\right)}$$

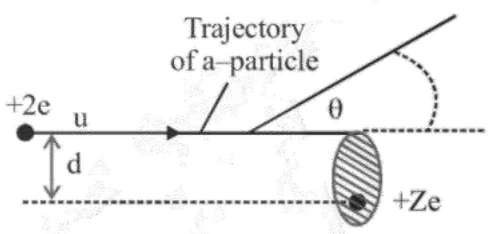


8.4 Impact parameter

The scattering of an alpha particle from the nucleus of an atom is dependent upon the impact parameter.

Impact Parameter of the alpha particle refers to the perpendicular distance of the velocity vector of the alpha particle from the centre of the nucleus, when it is far away from the atom. It is denoted by b and expressed as

$$b = \frac{1}{4\pi\varepsilon_0} \frac{Ze^2 \cot\theta/2}{\left(\frac{1}{2}mu^2\right)}$$



8.5 Discussion

The following conclusions can be drawn from the above equation:

1. When the impact parameter b is large, then $\cot \theta/2$ is also large i.e., the angle of scattering is small and vice-versa.
   Thus, when an α particle has a large impact parameter, it gets scattered through a very small angle and can practically go without any deviation. On the other hand, when the α particle has a small impact parameter, it would be scattered through a large angle.
2. If the impact parameter b is zero, then,
   $\cot\theta/2 = 0 \Rightarrow \theta/2 = 90^{\circ} \Rightarrow \theta = 180^{\circ}$

9. PHOTON

A photon refers to a packet of energy. It possesses energy given by, $E = h\nu$.
Where, $h = 6.62\times10^{34}\,Js$ is the Plank’s constant and ν is the frequency of the photon. When λ is wavelength of the photon, then, $c = \nu\lambda$.
Here, $c = 3\times10^{8}\,ms^{-1}$ is the velocity of light.
Clearly, $E = h\nu = hc/\lambda$
Energy of a photon is generally expressed in electron volt (eV).
$1eV = 6 \times 10^{19} J$
The bigger units are keV and MeV.
$1keV = 1.6\times10^{16} J$ and $1MeV = 1.6\times10^{13} J$

10. BOHR ATOMIC MODEL

Bohr considered the Rutherford model of the atom and added a few arbitrary conditions in it. These conditions are referred to as his postulates:

1. The electron in a stable orbit does not radiate energy. i.e., $\frac{mv^2}{r} = \frac{kZe^2}{r^2}$.
2. A stable orbit is that in which the angular momentum of the electron about nucleus is an integral (n) multiple of $\frac{h}{2\pi}$ i.e., $mvr = n\frac{h}{2\pi}; n = 1, 2, 3, ... (n \neq 0)$.
3. The electron can absorb or radiate energy only when the electron jumps from a lower to a higher orbit or falls from a higher to a lower orbit.
4. The energy emitted or absorbed is a light photon of frequency ν and of energy, $E = h\nu$.

10.1 For Hydrogen atom: $(Z = \text{atomic number} = 1)$

1. L_n = angular momentum in the n^{th} orbit $= n\frac{h}{2\pi}$
2. r_n = radius of n^{th} circular orbit $= (0.529\ A^o)n^2$ $(1A^o = 10^{-10}m)$

   $\Rightarrow r_n \propto n^2$
3. E_n = Energy of the electron in the n^{th} orbit $= \frac{-13.6eV}{n^2}$

   $\Rightarrow E_n \propto \frac{1}{n^2}$

   Note: Total energy of the electron in an atom is negative, mentioning that it is bound.

   Binding energy $(B.E)_n = -E_n = \frac{13.6V}{n^2}$
4. $E_{n_2} - E_{n_1}$ = Energy emitted when an electron jumps from $n_2{}^{th}$ orbit to $n^{th}{}_1$ orbit $(n_2 > n_1)$

   $$\Rightarrow \Delta E = (13.6ev)\left[\frac{1}{n_1^2} - \frac{1}{n^2{}_2}\right]$$

   $$\Rightarrow \Delta E = h\nu$$

   where,
   ν = frequency of spectral line emitted.
   $\frac{1}{\lambda} = \nu =$ wave number [number of waves in unit length]

$$\Rightarrow \nu = R\left[\frac{1}{n^2{}_1} - \frac{1}{n^2{}_2}\right]$$

where, $R =$ Rydberg's constant for hydrogen $= 1.097 \times 10^7 \, m^{-1}$

5. For hydrogen like atom/species of atomic number Z:

$$r_{nz} = \frac{\text{Bohr radius}}{Z} n^2 = \left(0.529A^o\right)\frac{n^2}{Z}$$

$$E_{nz} = (-13.6)\frac{Z^2}{n^2}ev$$

$R_z = RZ^2$ – Rydberg's constant for the element of atomic number Z.

Note: When motion of the nucleus is also considered, then m is replaced by μ, where

$$\mu = \text{reduced mass of electron-nucleus system} = \frac{mM}{(m+M)}$$

In this case, $E_n = (-13.6ev)\dfrac{Z^2}{n^2}\dfrac{\mu}{m_e}$

10.2 Spectral Series

1. Lyman Series: (Landing orbit $n = 1$)

Ultraviolet region $\bar{\nu} = R\left[\frac{1}{1^2} - \frac{1}{n_2{}^2}\right]; n_2 > 1$

2. Balmer Series: (Landing orbit $n = 2$)

Visible region $\bar{\nu} = R\left[\frac{1}{2^2} - \frac{1}{n_2{}^2}\right]; n_2 > 2$

3. Paschen Series: (Landing orbit $n = 3$)

In the near infrared region $\bar{\nu} = R\left[\frac{1}{3^2} - \frac{1}{n_2{}^2}\right]; n_2 > 3$

4. Bracket series: (Landing orbit $n = 4$)

In the mid infrared region $\bar{\nu} = R\left[\frac{1}{4^2} - \frac{1}{n_2{}^2}\right]; n_2 > 4$

5. Pfund series: (Landing orbit $n = 5$)

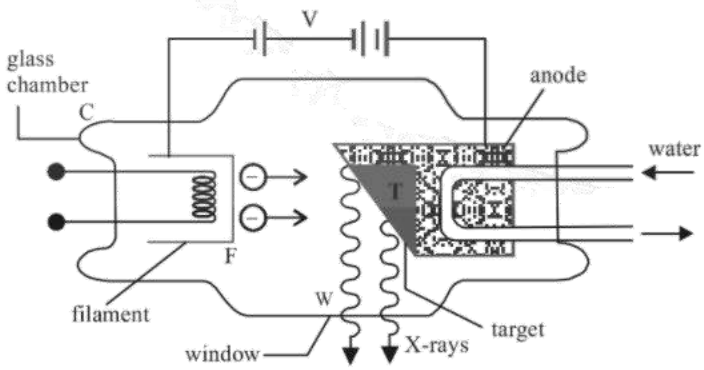
In far infrared region $\bar{\nu} = R\left[\frac{1}{5^2} - \frac{1}{n^2_2}\right]; n_2 > 5$

In all these series,
$n_2 = n_1 + 1$ is the α line
$n_2 = n_1 + 2$ is the β line
$n_2 = n_1 + 3$ is the γ line, and so on
Where $n_1 =$ Landing orbit

11. X-RAYS

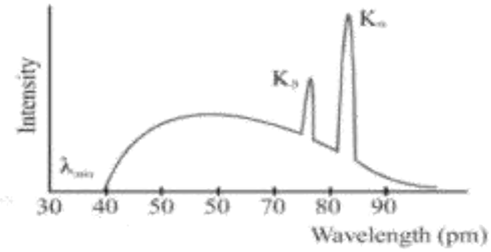
11.1 Production of X-rays

The following diagram gives a brief idea about the production of X-rays:



In the given X-ray tube, the electrons ejected from the metallic cathode travel towards the metal target anode with a voltage, which is accelerating in nature. The high energy electrons, which carry energies in eV interact with the atoms in the metal target. A few electrons reach very near to a nucleus in the target and suffer deviation by the electromagnetic interaction. It is during this process that the electron releases in the form of X-rays.

Now, if we plot a graph between the wavelength and intensity if X-ray emission, the looks like the following curve:



Considering this plot, it is understood that there is a minimum wavelength below which no X-ray is emitted. This is known as the cut off wavelength or the threshold wavelength.

For some sharply defined wavelengths, the intensity of X-rays is very large as marked by K_α and K_β in the plot. These X-rays are referred to as characteristic X-rays.

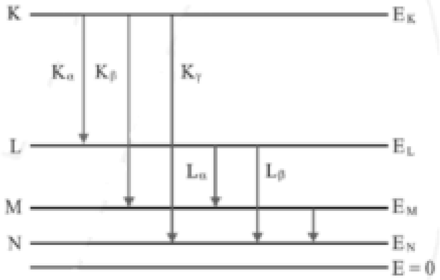
For other wavelengths, the intensity varies gradually and these X-rays are referred to as continuous X-rays.

An expression for threshold wavelength can be derived as:

$$\lambda = \frac{hc}{E} \Rightarrow \lambda_{min} = \frac{hc}{eV}$$

11.2 Characteristic X-rays

Now, consider the emission spectrum of characteristic X-rays as follows:



For K_α emission lines, threshold wavelength turns out to be

$$\lambda = \frac{hc}{E_K - E_L}$$

For K_β emission lines, threshold wavelength turns out to be

$$\lambda = \frac{hc}{E_L - E_M}$$

11.3 Moseley's law

It states that $\nu = A(Z-b)^2$ where, ν is the frequency of the X-ray emission line; A is the Rydberg frequency; b is another constant which is dependent on the kind of line and Z is the atomic number.

The variation of frequency with position number is as shown in the diagram below: