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Nuclear Structure

Syllabus : *Composition and size of nucleus.*

1. Composition of Nucleus

Proton-electron Hypothesis : As we have read, Rutherford's α-particle scattering experiment showed that the whole positive charge and almost the whole mass of an atom is concentrated in an extremely small space at the centre of the atom. This space is called the 'nucleus' of the atom and its diameter is of the order of 10^{-15} m. Electrons revolve round the nucleus in certain definite orbits. The negative charge of all the electrons is equal to the positive charge of the nucleus, the atom as a whole thus being neutral in its normal state.

In 1919, Rutherford discovered the proton. The mass of proton is equal to the mass of hydrogen nucleus and its charge is $+e$, that is, it has a positive charge equal to the (negative) electronic charge. The mass of electron is negligible as compared to the mass of proton. Looking at these facts, it was thought that the atomic nucleus was constituted of protons and electrons and these particles were jointly responsible for the positive charge and the mass of the nucleus. For example, the mass of helium nucleus is about 4 times the mass of proton, but the charge on it is only $+2e$. So, it was thought that helium nucleus has 4 protons and 2 electrons. (Around it, 2 more electrons revolve in orbits, whose total negative charge $-2e$ neutralises the $+2e$ charge of the nucleus). This proton-electron hypothesis however, faced a number of theoretical difficulties.

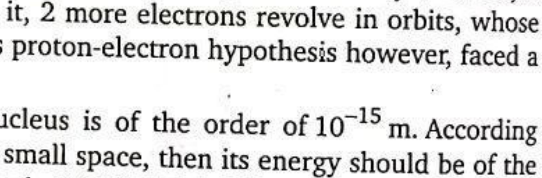
Shortcomings in Proton-electron Hypothesis : (i) The size of the nucleus is of the order of 10^{-15} m. According to the uncertainty principle, if an electron is to remain confined in such a small space, then its energy should be of the order of 100 MeV. But the energy of β-particles emitted from the nucleus is only 2-3 MeV. This difference of energy clearly indicates that electrons cannot exist in the nucleus.

(ii) If electrons exist in the nucleus, then the magnetic moment of the nucleus cannot be less than the magnetic moment of electron. But the magnetic moment of the nucleus is only about one-thousandth part of electron's magnetic moment. This also shows that electrons are not present in the nucleus.

(iii) Assuming the presence of electrons in the nucleus, the calculated angular momentum of the nucleus is different from its experimental value.

Proton-neutron Hypothesis : In 1932, neutron was discovered. Neutron is uncharged but its mass is nearly equal to the mass of proton. These properties of neutron, combined with the properties of proton, fit to the properties of nucleus. Hence, now we assume that ***nucleus has protons and neutrons.*** The protons give positive charge to the nucleus, while protons and neutrons together give it mass. The total number of protons and neutrons is equal to the integral value of the atomic mass and is called 'atomic mass number'. The number of protons is called the 'atomic number'. The place of an element in the periodic table is decided by its atomic number only.

The charge $(+e)$ and mass of hydrogen nucleus are exactly equal to those of a proton. So, there is only 1 proton in hydrogen nucleus (Fig. 1). Thus, the atomic number of hydrogen is 1 and its mass number is also 1. The deuterium (heavy hydrogen) nucleus (called deuteron) has charge $+e$, but its mass is nearly 2 times the mass of proton. Hence, it has 1 proton and 1 neutron. Thus, the atomic number of deuterium is 1 and its mass number is 2. The helium nucleus has charge $+2e$ but its mass is nearly 4 times the mass of proton. Hence, helium nucleus has 2 protons and 2 neutrons. Thus, the atomic number of helium is 2 and its mass number is 4. The lithium nucleus has charge $+3e$, but its mass is nearly 7 times the mass of proton. Hence, its nucleus has 3 protons and 4 neutrons. Thus, the atomic number of lithium is 3 and its mass number is 7. In general, if the atomic number of an atom is Z and its mass



(Fig. 1)

number is A, then its nucleus contains Z protons and $(A - Z)$ neutrons. If the atomic number of the atom X be Z and its mass-number be A, then this atom is written as $_Z X^A$. ***The nuclear particles (protons and neutrons) are also called 'nucleons'.****

2. Nuclear Size, Shape and Density

Nuclear Size : Rutherford's experiments on the scattering of α-particles by thin metallic foils provided a rough estimate of the size of atomic nucleus ($\approx 10^{-15}$ m). Since, then many scattering experiments using energetic electrons and neutrons as the scattering particles have been performed to determine the size of the nucleus. These experiments show that *the volume of a nucleus is directly proportional to the number of nucleons in it,* which is its mass number A. Thus, if R is the radius of a nucleus, (assumed spherical), then its volume is $(4/3)\,\pi R^3$ and

$$(4/3)\,\pi R^3 \propto A$$

or

$$R \propto A^{1/3}$$

or

$$\boxed{R = R_0 A^{1/3}}$$

where R_0 is an empirical constant whose value is experimentally found to be roughly 1.2×10^{-15} m. Since the mass number A is different for different atoms, ***nuclei of different atoms have different radii.***

The nuclear radii are conveniently expressed in fermi, where

$$1 \text{ fermi (F)} = 10^{-15} \text{ m.}$$

Thus,

$$R = 1.2\, A^{1/3} \text{ F}.$$

Nuclear Shape : For almost all purposes, nuclei are regarded as 'spherical'. Certain nuclei, however, deviate from sphericity, but the deviation is only about 10%.

Nuclear Density : Let m be the average mass of a nucleon and A the mass number (number of nucleons) of a nucleus. Then, the mass of the nucleus is

$$M = mA.$$

If R is the radius of the nucleus, then its volume is

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi (R_0\, A^{1/3})^3 = \frac{4}{3}\pi R_0^{\,3} A.$$

∴ Density of the nucleus is

$$\rho = \frac{M}{V} = \frac{mA}{\frac{4}{3}\pi R_0^{\,3} A} = \frac{3m}{4\pi R_0^{\,3}}.$$

Thus, the density is independent of A. It means that ***the density of the nuclei of all atoms is almost same.*** Taking $m = 1.67 \times 10^{-27}$ kg and $R_0 = 1.2 \times 10^{-15}$ m, we get

$$\rho = \frac{3 \times (1.67 \times 10^{-27} \text{ kg})}{4 \times 3.14 \times (1.2 \times 10^{-15} \text{ m})^3} \approx 2 \times 10^{17} \text{ kg m}^{-3}$$

Which is 10^{13} to 10^{14} times the density of ordinary matter, say water, for which $\rho = 1 \times 10^3$ kg m^{-3}. Thus, nucleus is very densely packed.

The nuclear densities are found in neutron stars in the universe.

3. Classification of Nuclei : Isotopes, Isobars and Isotones

The nuclei have been classified on the basis of the number of protons (atomic number) or the total number of nucleons (mass number) in them :

(a) Isotopes (or Isoprotons) : *The atoms of an element whose nuclei have the same number of protons but different number of neutrons are called the 'isotopes' of that element.* In other words, different isotopes of an element have the same atomic number (Z) but different mass number (A). Because of the same atomic number, the isotopes of an element have the same place in the periodic table. Almost every element has isotopes. Krypton has 6 and tin has 10 isotopes. The isotopes of some elements are the following :

hydrogen :	$_1H^1$, $_1H^2$, $_1H^3$
oxygen :	$_8O^{16}$, $_8O^{17}$, $_8O^{18}$
neon :	$_{10}Ne^{20}$, $_{10}Ne^{21}$, $_{10}Ne^{22}$

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* In an atom, the number of protons in its nucleus is equal to the number of electrons around the nucleus. The atom, in which the number of protons and electrons are different, is called 'ion'. If number of electrons is less than protons, it is called positive ion; and if more, then it is a negative ion.

** To give an idea about the density of matter in the nucleus, let us compare a 1 m × 1 m × 1 m of nuclear matter to things we experience in day-to-day life. So, this nuclear piece will be 2×10^{17} kg. In comparison, a Boeing 747 plane is only about 2×10^5 kg. Even a whole city will weigh less than this nuclear piece.

chlorine : $_{17}Cl^{35}$, $_{17}Cl^{37}$
uranium : $_{92}U^{235}$, $_{92}U^{238}$

The element hydrogen has three isotopes, each having atomic number 1 but their mass numbers are 1, 2 and 3. $_1H^1$ nucleus has 1 proton only, $_1H^2$ nucleus has 1 proton and 1 neutron, $_1H^3$ nucleus has 1 proton and 2 neutrons. The element oxygen has 3 isotopes, each with atomic number 8, but mass numbers are 16, 17 and 18. The first isotope has 8 protons and 8 neutrons, the second has 8 protons and 9 neutrons, while the third has 8 protons and 10 neutrons.

The element chlorine has two isotopes having mass numbers 35 and 37. In nature, these isotopes are found in the ratio 75.4% and 24.6%. When chlorine is prepared in the laboratory, its atomic mass is found to be 35.5 :

$$(35 \times 0.754) + (37 \times 0.246) = 35.5.$$

Thus, all those elements whose atomic masses are in fraction, are mixtures of two or more isotopes. The isotopes have integral atomic masses.

Special Features of Isotopes : (i) All isotopes of an element have the same number of electrons (an atom has equal number of electrons and protons). Therefore, chemical properties of different isotopes of an element are same.

(ii) The mass numbers (that is, number of nucleons) of different isotopes of an element are different. Hence, their physical properties are not the same.

(iii) As chemical properties are same, two isotopes of the same element cannot be separated by any chemical process. To separate them, physical processes based on atomic mass, like gaseous diffusion, are used.

(iv) Among isotopes of the same element, some may be stable and some radioactive. This is so because of the difference in their nuclear structure. For example, $_6C^{12}$ is stable, while $_6C^{14}$ is radioactive. Similarly, $_{11}Na^{23}$ is stable, while $_{11}Na^{24}$ is radioactive.

(b) Isobars : ***The nuclei which have the same number of nucleons, but different number of protons and different number of neutrons are called 'isobars'.*** Their atomic numbers (Z) are different, but mass number (A) is same. Therefore, they have different places in the periodic table and differ in chemical properties also. Since, in isobars the numbers of fundamental particles are different, they differ in physical properties also. The nuclei of isobars belong to different elements. Some examples of isobars are

$$_1H^3 \text{ and } _2He^3, \; _6C^{14} \text{ and } _7N^{14}, \; _8O^{17} \text{ and } _9F^{17}.$$

The daughter nucleus remaining after the emission of β-particle is an isobar of the parent nucleus.

(c) Isotones : ***The nuclei having equal number of neutrons are called 'isotones'.*** For them, both the atomic number (Z) and the mass number (A) are different, but the value of ($A - Z$) is same. Some examples of isotones are

$$_3Li^7 \text{ and } _4Be^8, \; _1H^3 \text{ and } _2He^4, \; _{11}Ne^{23} \text{ and } _{12}Mg^{24}.$$

4. Nuclear Forces

In nucleus, the positively-charged protons and the uncharged neutrons are held together in an extremely small space ($\approx 10^{-15}$ m) in spite of the fact that the electrostatic repulsion between two protons is about 10^{36} times stronger than the gravitational attraction between two nucleons. Obviously, there are some strong attractive forces operating within the nucleus which bind protons to protons (p-p forces), neutrons to neutrons (n-n forces) and protons to neutrons (p-n forces), thus keeping the nucleus intact. These are called "nuclear forces". Experimental evidence lead to the following properties of the nuclear forces :

(i) Nuclear Forces are Primarily Attractive : The overall effect of the nuclear forces is attractive, otherwise the nucleus would be disrupted under the electrostatic repulsion among the protons. (However, there is a repulsive component also in nuclear forces, because an exclusively attractive force would lead to a collapse of the nucleus.)

(ii) Nuclear Forces are Non-electric : The nuclear forces cannot be of an electrical nature. If it were so, the protons would repel one another, thus leading to nuclear disruption.

(iii) Nuclear Forces are Non-gravitational : If the gravitational forces between the nucleons are calculated, they are found to be about 10^{-40} times than the attractive forces demanded. Thus, the nuclear forces cannot be gravitational in origin.

(iv) Nuclear Forces are Extremely Strong : The study of simplest stable nuclei, like $_1H^2$ shows that the forces holding the nucleons together must be very strong. In fact, they constitute by far the strongest class of forces known.

(v) Nuclear Forces are Extremely Short-range Forces : They become operative only when the distance between two nucleons is a small multiple of 10^{-15} m. They do not exist when the distance is appreciably larger than 10^{-15} m and become repulsive when the distance is appreciably smaller than 10^{-15} m.

(vi) Nuclear Forces are Charge-independent : The nuclear forces make no distinction between neutrons and protons. Experiments involving the scattering of protons and neutrons show that the (attractive) nuclear forces existing between protons and protons (p-p forces), between neutrons and neutrons (n-n forces), and between protons and neutrons (p-n forces) are all essentially the same in magnitude.

(vii) Nuclear Forces are Spin-dependent : The force between two nucleons having parallel spins is greater than that between two nucleons having antiparallel spins.

(viii) Nuclear Forces have the Property of Saturation : This means that in the nucleus, any one nucleon interacts only with nucleons nearest to it (*not* with all the other nucleons of the nucleus). This is apparent from the fact that the average binding energy per nucleon is almost same for most of the nuclei.

Stability of Nucleus : The stability of a nucleus is decided by the 'relative' number of protons and neutrons present in the nucleus. The nuclei of lighter elements (except hydrogen) have equal, or nearly equal, number of protons and neutrons. In these nuclei, the very strong attractive nuclear forces completely overcome the electrical repulsive forces acting between the protons. Hence, the lighter elements remain stable. As we move towards the heavier elements, the number of protons and neutrons both increase in their nuclei, but the number of neutrons increases more rapidly compared to the number of protons. In iron the number of neutrons is nearly 20% more than the number of protons, while in uranium neutrons are nearly 50% more. Since, the (electrical) repulsive forces act between every pair of protons, whereas the nuclear attractive forces (being short-range) are active only between nucleons extremely close to each other, therefore the total electrical repulsive force rises more rapidly compared to the nuclear attractive force. As a result, the stability of nucleus goes on decreasing. As the number of protons (also of neutrons) increases, the stability of the nucleus decreases more and more. This is the reason that all elements heavier than lead (wherein number of protons is more than 82) are unstable. They continue radioactive emission and are converted into lighter elements. This is why only very heavy elements are radioactive.

Yukawa's Meson Theory of Nuclear Forces : The origin of the attractive, non-electrical, non-gravitational, but strongest short-range forces between nucleons remained a mystery for a long time. A Japanese scientist Yukawa, in 1935, predicted a new particle now called 'π-meson' (which was later on actually discovered in cosmic radiation) and held it responsible for the origin of nuclear forces. The rest mass of a π-meson is about 200 times the rest-mass of an electron but less than the mass of proton or neutron. Mesons are of three types, positively charged, negatively charged and uncharged (π^+, π^-, π^0). The magnitude of charge on a charged meson is equal to electronic charge. According to Yukawa, there is a cloud of π-mesons around every nucleon (proton and neutron). The difference between proton and neutron is only due to different structures of meson clouds around them. There is a continuous exchange of π-mesons between protons and neutrons due to which they continue to be converted into one another.

When a π^+ meson jumps from a proton to a neutron, the proton is converted into a neutron and the neutron is converted into a proton :

$$p - \pi^+ \rightarrow n; \quad n + \pi^+ \rightarrow p.$$

Conversely, when a π^- meson jumps from a neutron to a proton, the neutron is converted into a proton and the proton is converted into a neutron :

$$n - \pi^- \rightarrow p; \quad p + \pi^- \rightarrow n.$$

The exchange of π^+ and π^- mesons between protons and neutrons is responsible for the origin of nuclear forces between them. Similarly, nuclear forces between two protons, and between two neutrons, are generated by a continuous exchange of π^0-mesons between them. Thus, ***the basis of nuclear forces is the exchange of mesons and hence these are also called 'exchange forces'.***

Although a neutron outside the nucleus is an unstable particle but inside the nucleus the neutrons and protons are continuously converted into one another and so a proton-neutron pair is stable in dynamic equilibrium.

According to the modern concept, all the forces, strong, electrical, weak and gravitational forces are exchange forces. Electrical forces between two charged particles are generated by exchange of photons. A new particle 'graviton' has been assumed to be responsible for the origin of gravitational forces between two particles of matter.

5. Nuclear Reactions

A nuclear reaction is a strong interaction of an atomic nucleus with an elementary particle, resulting in the formation of a new nucleus and one or more new particles. It can be represented by an equation :

$$X + a \longrightarrow Y + b$$

where X is the initial nucleus, a the initial particle, Y the final nucleus and b the final particle. In short form, it can be written as

$$X \ (a, b) \ Y.$$

The particles involved in the reaction are written in brackets, first the initial particle and then the final particle. The particles a and b may be α-particle (${}_2He^4$), proton (${}_1H^1$ or p), deuteron (${}_1H^2$ or d), neutron (n), γ-ray photon (γ), etc.

Nuclear reactions are attended by liberation or absorption of energy, known as 'reaction energy' or 'disintegration energy'.

The first nuclear reaction, which led to the discovery of proton (${}_1\mathrm{H}^1$) was

$$ {}_7\mathrm{N}^{14} + {}_2\mathrm{He}^4 \longrightarrow {}_8\mathrm{O}^{17} + {}_1\mathrm{H}^1 $$

In this reaction, a nitrogen nucleus hit by an α-particle is converted into an oxygen isotope nucleus and a proton is emitted. This reaction is called alpha-proton (α, *p*) reaction.

In every nuclear reaction; the charge, the total number of nucleons (protons and neutrons) and the total mass *plus* energy is conserved. Other examples of nuclear reactions are :

$$\begin{array}{lcllcll}
{}_5\mathrm{B}^{11} & + & {}_2\mathrm{He}^4 \longrightarrow & {}_7\mathrm{N}^{14} & + & {}_0n^1 & (\alpha, n) \\
{}_4\mathrm{Be}^9 & + & {}_1\mathrm{H}^1 \longrightarrow & {}_3\mathrm{Li}^6 & + & {}_2\mathrm{He}^4 & (p, \alpha) \\
{}_8\mathrm{O}^{18} & + & {}_1\mathrm{H}^1 \longrightarrow & {}_9\mathrm{F}^{18} & + & {}_0n^1 & (p, n) \\
{}_6\mathrm{C}^{12} & + & {}_1\mathrm{H}^2 \longrightarrow & {}_6\mathrm{C}^{13} & + & {}_1\mathrm{H}^1 & (d, p) \\
{}_3\mathrm{Li}^6 & + & {}_0n^1 \longrightarrow & {}_1\mathrm{H}^3 & + & {}_2\mathrm{He}^4 & (n, \alpha) \\
{}_{13}\mathrm{Al}^{27} & + & {}_0n^1 \longrightarrow & {}_{12}\mathrm{Mg}^{27} & + & {}_1\mathrm{H}^1 & (n, p) \\
{}_1\mathrm{H}^2 & + & \gamma \longrightarrow & {}_1\mathrm{H}^1 & + & {}_0n^1 & (\gamma, n)
\end{array}$$