Atoms and Nuclei

- Atom, as a whole, is electrically neutral and therefore contains equal amount of positive and negative charges.
- In Thomson's model, an atom is a spherical cloud of positive charges with electrons embedded in it.
- In Rutherford's model, most of the mass of the atom and all its positive charge are concentrated in a tiny nucleus (typically one by ten thousand the size of an atom), and the electrons revolve around it.
- Rutherford nuclear model has two main difficulties in explaining the structure of atom: (a) It predicts that atoms are unstable because the accelerated electrons revolving around the nucleus must spiral into the nucleus. This contradicts the stability of matter. (b) It cannot explain the characteristic line spectra of atoms of different elements.

- Atoms of each element are stable and emit characteristic spectrum. The spectrum consists of a set of isolated parallel lines termed as line spectrum. It provides useful information about the atomic structure.

- The atomic hydrogen emits a line spectrum consisting of various series. The frequency of any line in a series can be expressed as a difference of two terms;

    - Lyman series: $v = Rc\{ (1/1^2) – (1/n^2)\}$; $n = 2,3,4..$
    - Balmer Series: $v = Rc\{ (1/2^2) – (1/n^2)\}$; $n = 3,4,5..$
    - Paschen Series: $v = Rc\{ (1/3^2) – (1/n^2)\}$; $n = 4,5,6..$
    - Brackett Series: $v = Rc\{ (1/4^2) – (1/n^2)\}$; $n = 5,6,7..$
    - Pfund Series: $v = Rc\{ (1/5^2) – (1/n^2)\}$; $n = 6,7,8..$
- To explain the line spectra emitted by atoms, as well as the stability of atoms, Niel’s Bohr proposed a model for hydro genic (single electron) atoms. He introduced three postulates and laid the foundations ofquantum mechanics:

- In a hydrogen atom, an electron revolves in certain stable orbits(called stationary orbits) without the emission of radiant energy.

- The stationary orbits are those for which the angular momentum is some integral multiple of $h/2\pi$. (Bohr's quantisation condition.) That is $L = nh/2\pi$, where n is an integer called a quantum number.

- The third postulate states that an electron might make a transition from one of its specified non-radiating orbits to another of lower energy. When it does so, a photon is emitted having energy equal to the energy difference between the initial and final states. The frequency (ν) of the emitted photon is then given by

  $h\nu = E_i – E_f$

  An atom absorbs radiation of the same frequency the atom emits, in which case the electron is transferred to an orbit with a higher value of n.

$Ei + h\nu = Ef$

- As a result of the quantisation condition of angular momentum, theelectron orbits the nucleus at only specific radii. For a hydrogen atomit is given by

  $r_n = (n^2/m)(h/2\pi)^2 (4\,\pi\varepsilon_0/e^2)$

  The total energy is also quantized as

  $E_n = -\,(me^4/8n^2\,\varepsilon_0^2\,h^2) = -\,13.6\ \text{eV}/n^2$

  The n = 1 state is called ground state. In hydrogen atom the ground state energy is –13.6 eV. Higher values of n correspond to excited states (n > 1). Atoms are excited to these higher states by collisions with other atoms or electrons or by absorption of a photon of right frequency.

- De Broglie’s hypothesis that electrons have a wavelength $\lambda = h/mv$ gave an explanation for Bohr’s quantised orbits by bringing in the wave particle duality. The orbits correspond to circular standing waves in which the circumference of the orbit equals a whole number of wavelengths.
- Bohr’s model is applicable only to hydro genic (single electron) atoms. It cannot be extended to even two electron atoms such as helium. This model is also unable to explain for the relative intensities of the frequencies emitted even by hydro genic atoms.

Nuclei

- An atom has a nucleus. The nucleus is positively charged. The radiusof the nucleus is smaller than the radius of an atom by a factor of10^4. More than 99.9% mass of the atom is concentrated in the nucleus.
- On the atomic scale, mass is measured in atomic mass units (u). Bydefinition, 1 atomic mass unit (1u) is 1/12 th mass of one atom of 12C;

  1u = 1.660563 × 10–27 kg.
- A nucleus contains a neutral particle called neutron. Its mass is almostthe same as that of proton
- The atomic number Z is the number of protons in the atomic nucleusof an element. The mass number A is the total number of protons andneutrons in the atomic nucleus; $A = Z+N$; Here N denotes the numberof neutrons in the nucleus.
- *A* nuclear species or a nuclide is represented as ${}^{A}X_{Z}$, where X is thechemical symbol of the species.

- Nuclides with the same atomic number *Z*, but different neutron number*N* are called *isotopes*. Nuclides with the same *A* are *isobars* and thosewith the same *N* are *isotones*.
- Most elements are mixtures of two or more isotopes. The atomic massof an element is a weighted average of the masses of its isotopes. Themasses are the relative abundances of the isotopes.
- A nucleus can be considered to be spherical in shape and assigned aradius. Electron scattering experiments allow determination of thenuclear radius; it is found that radii of nuclei fit the formula

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

  where R_0 = a constant = 1.2 fm. This implies that the nuclear density is independent of A. It is of the order of 1017 kg/m3.
- Neutrons and protons are bound in a nucleus by the short-range strong nuclear force. The nuclear force does not distinguish between neutron and proton.
- The nuclear mass M is always less than the total mass, Σm, of its constituents. The difference in mass of a nucleus and its constituents is called the mass defect,

  $\Delta M = (Z\, m_p + (A - Z)m_n) - M$

Using Einstein’s mass energy relation, we express this mass difference in terms of energy as

$\Delta E_b = \Delta M c^2$

The energy ΔE_brepresents the binding energy of the nucleus. In the mass number range A = 30 to 170, the binding energy per nucleon is nearly constant, about 8 MeV/nucleon.

Energies associated with nuclear processes are about a million timeslarger than chemical process.

- The Q-value of a nuclear process is

  Q = final kinetic energy – initial kinetic energy.

  Due to conservation of mass-energy, this is also,

  $Q = (\text{sum of initial masses} - \text{sum of final masses})c^2$

- Radioactivity is the phenomenon in which nuclei of a given speciestransform by giving out α or β or γ rays; α-rays are helium nuclei; β-rays are electrons. γ-rays are electromagnetic radiation of wavelengthsshorter than *X*-rays;
- Law of radioactive decay : $N(t) = N(0)\, e^{-\lambda t}$

  where λ is the decay constant or disintegration constant.

- The half-life $T_{1/2}$ of a radionuclide is the time in which N has beenreduced to one-half of its initial value. The mean life τ is the time atwhich N has been reduced to e^{-1} of its initial value.

  $T_{1/2} = (\ln 2/ \lambda) = \tau \ln 2$
- Energy is released when less tightly bound nuclei are transmuted intomore tightly bound nuclei. In fission, a heavy nucleus like $_{92}U^{235}$ breaksinto two smaller fragments.
- The fact that more neutrons are produced in fission than are consumedgives the possibility of a chain reaction with each neutron that isproduced triggering fission. The chain reaction is uncontrolledand rapid in a nuclear bomb explosion. It is controlled and steady ina nuclear reactor. In a reactor, the value of the neutron multiplicationfactor k is maintained at 1.
- In fusion, lighter nuclei combine to form a larger nucleus. Fusion ofhydrogen nuclei into helium nuclei is the source of energy of all starsincluding our sun.