

CEMA-CC-2-4-TH

INORGANIC CHEMISTRY-2

Radioactivity

Nuclear stability and nuclear binding energy. Nuclear forces: meson exchange theory.

Nuclear models (elementary idea): Concept of nuclear quantum number, magic numbers.

Nuclear Reactions: Artificial radioactivity, transmutation of elements, fission, fusion and spallation.

Nuclear energy and power generation. Separation and uses of isotopes.

Radio chemical methods: principles of determination of age of rocks and minerals, radio carbon dating, hazards of radiation and safety measures.

Introduction

- Researches by J. J. Thomson, Dalton, Rutherford and Mosley showed that an atom is smallest but not the ultimate particle of the matter.
- An atom consists of subatomic particles mainly protons, neutrons and electrons, called fundamental particles.
- Besides these, mesons, positrons, neutrinos are also associated with the atomic structure.

Atomic number (Z):

The number of protons present in the nucleus of an atom is called atomic number.

- Atoms of the same element have the same atomic number.
- Isotopes have the same atomic number.
- Chemical properties of elements are periodic properties of its atomic number.
- Example: In Sodium atom there are 11 protons. Hence atomic number of Sodium is 11.

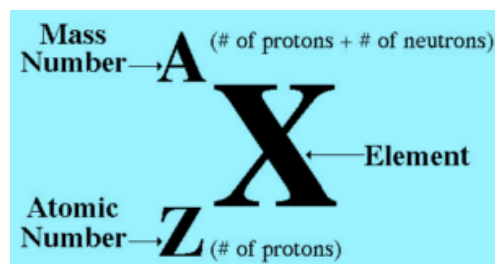
Neutron number (N):

The number of neutrons present in the nucleus of an atom is known as neutron number. It is denoted by N.

Mass number (M):

The total number of protons and neutrons present in the nucleus of an atom of the element is called mass number.

- It is denoted as A.
$$A = Z + N$$
- Atoms of the same element can have different mass numbers.
- Isobars have the same mass number.
- Chemical properties of elements are not periodic of its mass number.
- In Sodium atom, the total number of protons and neutrons is 23. Hence the mass number of Sodium is 23.

Representation of Atom in Symbol Form:**Isotopes:**

Different atoms of the same element having the same atomic number but having different mass numbers are known as isotopes.

- Examples: a) ${}_1\text{H}^1, {}_1\text{H}^2, {}_1\text{H}^3$ b) ${}_{17}\text{Cl}^{35}, {}_{17}\text{Cl}^{37}$
c) ${}_8\text{O}^{16}, {}_8\text{O}^{17}, {}_8\text{O}^{18}$ d) ${}_{92}\text{U}^{235}, {}_{92}\text{U}^{238}$
- So isotopes have the same number of protons but the different number of neutrons.
- Since they have the same atomic number they show same chemical properties.
- They occupy same positions in the periodic table.

Isobars:

Atoms of the different elements having a different atomic number but having same mass number are known as isobars.

- Examples: a) $_{18}\text{Ar}^{40}$, $_{19}\text{K}^{40}$, $_{20}\text{Ca}^{40}$ b) $_{6}\text{C}^{14}$, $_{7}\text{N}^{14}$ c) $_{82}\text{Pb}^{210}$, $_{83}\text{Bi}^{210}$
- So isobars have different number of protons and neutrons.
- Since they have the different atomic number they show different chemical properties.
- They occupy different positions in the periodic table.

Isotones:

Atoms of the different elements having the different atomic number, mass number but having same neutron number are known as isotones.

- Examples: $_{80}\text{Hg}^{198}$, $_{79}\text{Au}^{197}$
- Since they have different atomic number, they show different chemical properties.
- They occupy different positions in the periodic table.

❖ Nuclear Stability:

- The nucleus of an atom is extremely small. The radius of the nucleus is about 10^{-15} m. In such a small place protons and neutrons are held together.
- Protons are positively charged so they should get repelled. However the majority of the nuclei are stable. Hence there must be certain factors which affect nuclear stability.
- Some of the factors that affect nuclear stability are-
 - Nuclear forces.
 - Mass defect and binding energy.
 - Neutron to proton (N/Z or n/p ratio).
 - Odd and even number of nucleons.

Stability of Nucleus Due to Nuclear Forces:

- The forces which hold the nucleons together within the nucleus are called nuclear forces.
- These are short range forces.
- They are different from gravitation forces.

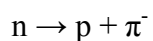
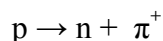
Explanation:

- The nucleus of an atom, except in the case of radioactive elements is extremely stable. The nucleus on account of its stability does not take part in the chemical reaction.
- There are forces between proton and proton (P-P), neutron (n-n) and even between proton and neutron (p-n). The force between proton and proton is repulsive in nature. In presence of such forces, the nucleons are kept together within the nucleus by some strong attraction forces. Thus a very high energy is required to break the nucleus to its constituent particles.
- The nature of nuclear binding forces is totally different from that of gravitational and electrostatic forces. Nuclear forces are stronger than gravitational and electrostatic forces.
- These nuclear binding forces are independent of charge and operate over the only very short distance of range 10^{-15} m. Hence they are short range forces.

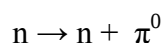
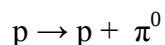
Origin of Nuclear Force:

Meson Exchange Theory:

- According to particle exchange theory proposed by Japanese scientist Yukawa, the nuclear forces arise from a constant exchange of particles called mesons between the nearby nucleons.
- As two atoms are held together by sharing of electrons, two nucleons or nuclear particles are held together by sharing of mesons (π).
- According to charge carried by them, Mesons are classified into three type- Positive charge mesons (π^+), Negative charge meson (π^-), Zero charge meson (π^0).
- Exchange of positive charge meson (π^+) and negative charge meson (π^-) accounts for the nuclear force between protons and neutrons. Transfer of charged meson converts a proton to neutron and neutron to proton.



- π^0 Mesons are exchanged between like particles such as p-p or n-n



- Due to the constant interaction between nucleons, an exchange force is developed called nuclear force which holds nucleons together inside nucleus of an atom with minimum potential energy. The greater the exchange force (nuclear force) the greater is the stability of the nucleus.
- Mass of π^+ and π^- is 273 times that of the electron. While that of π^0 is 264 times that of the electron. Mesons are unstable outside the nucleus.

❖ Stability of Nucleus Due to Nuclear Binding Energy:

Mass Defect:

The difference between the calculated mass due to nucleons and the actual observed isotopic mass of the nucleus is called the mass defect.

Mass defect is denoted by ' Δm .'

Explanation:

Consider ${}_Z X^A$ isotope

Let A be the mass number and Z be the atomic number of element A.

If m_p , m_e and m_n be the masses of proton, electron and neutron respectively, M_i be isotopic mass then,

Calculated mass, $M_{cal} = Z \times m_p + (A - Z) \times m_n$

Now mass defect (Δm) = Calculated mass – Observed mass

$$\Delta m = [Z \times m_p + (A - Z) \times m_n] - M_i$$

Mass of an electron is negligible. Hence it is not considered for calculation of mass defect.

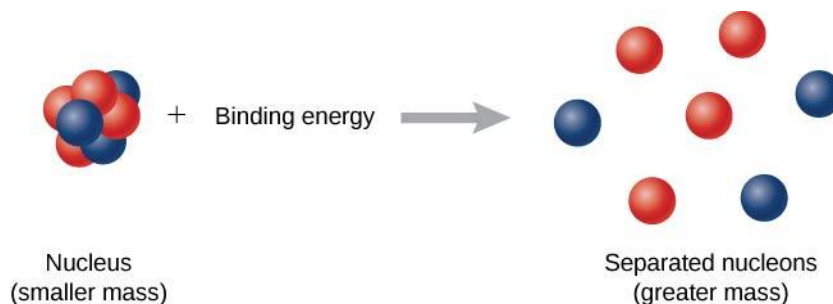
The mass equivalent to mass defect is converted into energy which is given by Einstein's energy equation

$$E = \Delta m \times C^2 \quad \text{where, } C = \text{speed of light in free space.}$$

This energy holds the nucleons together in the nucleus called nuclear binding energy. Hence nuclear stability is proportional to the mass defect.

Nuclear Binding Energy:

The energy equivalent to mass defect, which is required to break the nucleus into its isolated nucleons, is called nuclear binding energy.



It is denoted by E and is measured in MeV (million electron volts) or J (joule). It is obtained by multiplying mass defect in a.m.u by 931.

Therefore, Nuclear Binding Energy = Mass defect in a.m.u. $\times$ 931 MeV.

$$[1 \text{ eV} = 1.602 \times 10^{-19} \text{ Coulomb} \times 1 \text{ Volt} = 1.602 \times 10^{-19} \text{ Joule}$$

$$1 \text{ atomic mass unit or a.m.u} = 1.66 \times 10^{-27} \text{ kg}$$

$$\equiv 1.66 \times 10^{-27} \text{ kg} \times (2.9979 \times 10^8 \text{ ms}^{-1})^2$$

$$= 14.9191 \times 10^{-11} \text{ Joule}$$

$$\equiv 931.28 \text{ MeV }]$$

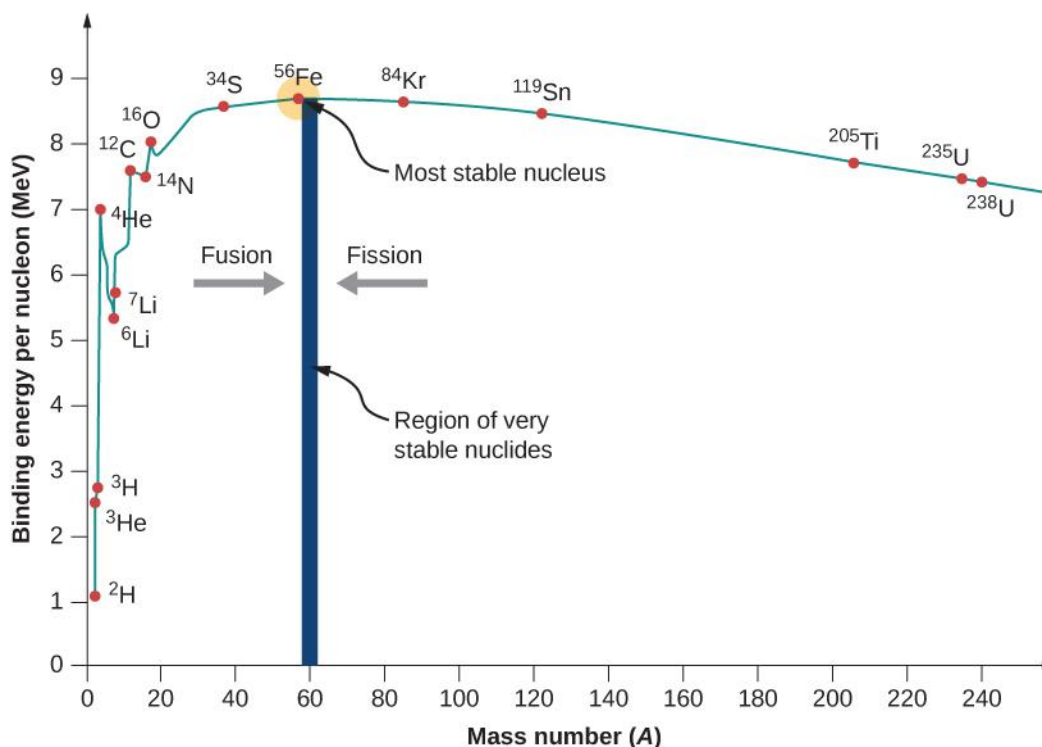
Nuclear Binding Energy Per Nucleon or Average Binding Energy:

It is the ratio of total nuclear binding energy to the total number of nucleus present in that isotope.

$$\text{Binding Energy Per Nucleon} = \frac{\text{Total Binding Energy}}{\text{Total Number of Nucleons}} = \frac{\Delta m \times 931}{A} \text{ MeV}$$

Nuclear Stability on the Basis of Nuclear Binding Energy:

Since binding energy is responsible for holding the nucleons. Nuclear stability is proportional to the nuclear binding energy. The more the binding energy, the greater is the nuclear stability. If we plot binding energy per nucleon in MeV against mass numbers (A) for different nuclei, a curve is obtained. The curve is called Binding Energy Curve. This curve represents the relative stability of the nuclei of the elements.



- The curve shows that the average binding energy rises sharply and then it is constant for a broad range and then it decreases slowly.
- It is observed that higher the binding energy per nucleon, greater is the stability of the nucleus.
- It is found that the stable nuclei have binding energy per nucleon between 8 and 8.8 MeV. Binding energy per nucleon for the majority of the elements lies between 8 - 8.8 MeV.
- Elements having a mass number less than 25 have low binding energy per nucleon. They show the tendency of nuclear fusion. Elements $^2\text{He}^4$, $^6\text{C}^{12}$ and $^8\text{O}^{16}$ lie above the curve, it indicates their greater stability.

- For elements having the mass number in the range 25 to 65, binding energy per nucleon smoothly increases from 7.5 MeV to 8.8 MeV. It attains maximum value for Fe. Due to extra stability Fe, Co and Ni form the core of the earth.
- For nuclei having the mass number in the range 65 to 160, binding energy per nucleon is almost constant at 8.5 MeV.
- For nuclei having the mass number beyond 160, the binding energy per nucleon decreases steadily and it becomes 8 MeV for ${}_{83}\text{Bi}^{209}$ and it reaches to 7.6 MeV for Uranium.
- Nuclei with the mass number more than 220 and having binding energy per nucleon less than 8 MeV are highly unstable and have a tendency of fission or natural radioactivity.
- Thus the nuclei having B.E. per nucleon in a range of 8 to 8.5 MeV are stable while those having B.E. per nucleons less than 8MeV are unstable or less stable.

Solve the Following Problems:

1. Calculate the mass defect of atom ${}_{17}\text{Cl}^{35}$. The experimental mass of ${}_{17}\text{Cl}^{35}$ is 34.968851 a.m.u. $M_{\text{H}} = 1.007825$ a.m.u. $M_{\text{n}} = 1.008665$ a.m.u.
2. Calculate the binding energy of the helium nucleus, given that its true mass defect is 0.030377 a.m.u. Also calculate the average binding energy per nucleon.
3. Calculate the Binding energy per nucleon of the ${}_{18}\text{Ar}^{40}$ nucleus. The experimental mass of ${}_{18}\text{Ar}^{40}$ is 39.962384 a.m.u. $M_{\text{H}} = 1.007825$ a.m.u. $M_{\text{n}} = 1.008665$ a.m.u.
4. For ${}_{6}\text{C}^{12}$, nuclear binding energy per nucleon is 7.683 MeV. Find the mass defect.