

# ESE 2024

UPSC ENGINEERING SERVICES EXAMINATION

## Preliminary Examination

### General Studies and Engineering Aptitude

### Basics of Material Science and Engineering

Comprehensive Theory *with* Practice Questions  
*and* ESE Solved Questions



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**ESE 2024 Preliminary Examination : Basics of Material Science and Engineering**

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1st Edition : 2016

2nd Edition : 2017

3rd Edition: 2018

4th Edition: 2019

5th Edition: 2020

6th Edition: 2021

7th Edition: 2022

**8th Edition: 2023**

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# Preface

The compilation of this book **Basics of Material Science and Engineering** was motivated by the desire to provide a concise book which can benefit students to understand the concepts of this specific topic of General Studies and Engineering Aptitude section.



**B. Singh** (Ex. IES)

This textbook provides all the requirements of the students, i.e. comprehensive coverage of theory, fundamental concepts and objective type questions articulated in a lucid language. The concise presentation will help the readers grasp the theory of this subject with clarity and apply them with ease to solve objective questions quickly. This book not only covers the syllabus of ESE in a holistic manner but is also useful for many other competitive examinations. All the topics are given the emphasis they deserve so that mere reading of the book clarifies all the concepts.

We have put in our sincere efforts to present detailed theory and MCQs without compromising the accuracy of answers. For the interest of the readers, some notes, do you know and interesting facts are given in the comprehensive manner. At the end of each chapter, sets of practice question are given with their keys and detailed explanations, that will allow the readers to evaluate their understanding of the topics and sharpen their question solving skills.

Our team has made their best efforts to remove all possible errors of any kind. Nonetheless, we would highly appreciate and acknowledge if you find and share with us any printing and conceptual errors.

It is impossible to thank all the individuals who helped us, but we would like to sincerely thank all the authors, editors and reviewers for putting in their efforts to publish this book.

With Best Wishes

**B. Singh**

CMD, MADE EASY Group

## Chapter 1

<b>Introduction .....</b>	<b>1</b>
1.1 Historical Perspective .....	1
1.2 Material Science .....	1
1.3 Classification of Materials.....	2
1.4 What is Material? .....	3
1.5 Engineering Needs of Material.....	3

## Chapter 2

<b>Chemical Bonding .....</b>	<b>5</b>
2.1 Basic Laws of Chemistry.....	5
2.2 Fundamental Concepts.....	6
2.3 Electrons in Atoms.....	7
2.4 The Periodic Table .....	7
2.5 Comparison of Alpha (a), Beta (b) and Gamma (g) Rays .....	8
2.6 Quantum Number.....	9
2.7 Electron Affinity .....	11
2.8 Electronegativity .....	11
2.9 Pauli's Exclusion Principle.....	11
2.10 Auf-bau Principle.....	12
2.11 Hund's Rule .....	12
2.12 Heisenberg Uncertainty Principle .....	12
2.13 Gay Lussac's Law of Gaseous Volumes .....	13
2.14 Dalton's Atomic Theory .....	13
2.15 Rutherford Model.....	13
2.16 Bohr Model .....	13
2.17 Sommerfeld's Model .....	14
2.18 De Broglie Wave Equation.....	14
2.19 Octet Rule .....	14
2.20 Boyle's Law (Pressure-Volume Relationship).....	15
2.21 Charles Law (Temperature-Volume Relationship).....	15
2.22 Gay-Lussac's Law (Pressure-Temperature Relationship).....	16
2.23 Avogadro Law (Volume-Amount Relationship).....	16
2.24 Ideal Gas Equation .....	17

2.25 Dalton's Law of Partial Pressures.....	17
2.26 Chemical Bonding.....	17
2.27 Ionic Bond.....	18
2.28 Covalent Bond .....	19
2.29 Metallic Bond.....	20
2.30 Comparison of Primary Bonds.....	21
2.31 Van der Waal Bond .....	21
2.32 Dispersion Bonds .....	22
2.33 Dipole Bonds.....	22
2.34 Hydrogen Bonds.....	23
2.35 Properties of Water (H <sub>2</sub> O) .....	23
2.36 Directional Bond.....	25
2.37 Non-directional Bond .....	25
2.38 Molecular Orbital Theory.....	25
2.39 Hybridization .....	26
<i>Objective Brain Teasers .....</i>	<i>28</i>

## Chapter 3

<b>Crystallography .....</b>	<b>31</b>
3.1 Introduction .....	31
3.2 Comparison of Crystalline and Noncrystalline Solids.....	31
3.3 Lattice Points, Space Lattice and Crystal Structures.....	32
3.4 Unit Cell and Primitive Unit Cell.....	33
3.5 Bravais Lattices.....	33
3.6 Cubic Crystal Structures.....	35
3.7 Hexagonal Closed Packing .....	38
3.8 Miller Indices.....	39
3.9 Interplanar Spacing.....	40
3.10 Crystal Imperfections.....	40
3.11 Point Imperfections.....	41
3.12 Line Defect.....	43
3.13 Surface Defect .....	45
3.14 Ionic Crystal Structure .....	46
3.15 Bragg's Law .....	47
3.16 Polymorphism and Allotropy.....	48
<i>Objective Brain Teasers .....</i>	<i>52</i>

## Chapter 4

### Electric Properties of Materials ..... 57

4.1	Introduction .....	57
4.2	Ohm's Law and Electrical Conductivity .....	58
4.3	Energy Band Structure in Solids.....	60
4.4	Classification of Materials based upon Energy Band Diagram.....	62
4.5	Electrical Resistivity of Metals.....	63
4.6	Thermal Conductivity of Metals–Wiedemann Franz law.....	64
4.7	Thermoelectric Phenomenon.....	65
4.8	Insulators .....	65
4.9	Dielectrics.....	67
4.10	Electric Dipole Moment and Polarization...	69
4.11	Types of Polarization .....	70
4.12	Phase Difference and Dielectric Loss .....	71
4.13	Polar Molecules.....	72
4.14	Nonpolar Materials .....	72
4.15	Other Electrical Characteristics of Materials .....	72
4.16	Use of Dielectrics .....	75
4.17	Semiconductor Materials .....	75
4.18	Electrons and Holes in an Intrinsic Semiconductor (Pure Semiconductor).....	76
4.19	Extrinsic Materials .....	76
4.20	Charge Densities in a Semiconductor .....	77
4.21	Electrical Properties of Semiconductors.....	78
4.22	Hall Effect .....	79
4.23	Thermistors.....	79
4.24	Photoconductors.....	80
	<i>Objective Brain Teasers</i> .....	82

## Chapter 5

### Magnetic Properties of Materials..... 86

5.1	Introduction .....	86
5.2	Magnetic Parameters .....	86
5.3	Classification of Magnetic Materials.....	87
5.4	Curie Temperature .....	92
5.5	Laws of Magnetic Materials .....	93
5.6	Domain Theory.....	94
5.7	Magnetisation Curve and Magnetic Hysteresis Loop .....	95
5.8	Soft Magnetic Materials .....	96
5.9	Hard Magnetic Materials .....	98

5.10	Magnetic Storage.....	100
5.11	Superconductivity.....	100
	<i>Objective Brain Teasers</i> .....	104

## Chapter 6

### Ceramics ..... 107

6.1	Introduction .....	107
6.2	Silicate Ceramics .....	108
6.3	Ceramics Used in Electrical Applications..	110
6.4	Stress-Strain Behavior of Ceramics .....	111
6.5	Properties of Ceramics .....	112
6.6	Glass.....	113
6.7	Piezoelectric Ceramics.....	114
6.8	Cement.....	114
6.9	Carbon.....	114
	<i>Objective Brain Teasers</i> .....	118

## Chapter 7

### Polymers..... 121

7.1	Introduction .....	121
7.2	Basic Definitions .....	121
7.3	General Characteristics of Polymer.....	123
7.4	Molecular Structure of Polymers .....	123
7.5	Different Types of Polymerizations Reactions.....	124
7.6	Co-polymer.....	125
7.7	Classification of Plastics .....	125
7.8	Thermoplastic Materials .....	126
7.9	Thermosetting Materials .....	128
7.10	Mechanical Behaviour of Plastics .....	131
7.11	Compounding Materials.....	131
7.12	Comparison of Polymers with Ceramics and Metals .....	132
7.13	Elastomer .....	132
7.14	Fibre .....	132
7.15	Coatings.....	133
7.16	Vulcanization .....	133
7.17	Stress-Strain Behavior of Polymers .....	134
7.18	Advanced Polymeric Materials .....	135
7.19	Crystallization of Polymers.....	135
	<i>Objective Brain Teasers</i> .....	139

## Chapter 8

### Composites ..... 143

8.1	Introduction .....	143
8.2	General Characteristics of Composites.....	143

8.3	Natural Composites .....	145
8.4	Particle-Reinforced Composites .....	145
8.5	Fibre-Reinforced Composites .....	147
8.6	Laminar Composites .....	148
8.7	Polymer-Matrix Composites (PMCs) .....	149
8.8	Fibre Phase.....	150
8.9	Matrix Phase.....	151
	<i>Objective Brain Teasers</i> .....	152

## Chapter 9

### **Mechanical Properties of Materials ..... 153**

9.1	Introduction .....	153
9.2	Normal Stress.....	153
9.3	Strain.....	154
9.4	Tension Test for Mild Steel.....	154
9.5	Common Terms of Mechanical Properties.....	156
9.6	Fracture .....	162
9.7	Hooke's Law .....	162
9.8	Elastic Constants.....	163
9.9	Difference between Linearly and Non-linearly Elastic Materials.....	164
9.10	Fatigue.....	164
	<i>Objective Brain Teasers</i> .....	168

## Chapter 10

### **Ferrous Metals ..... 171**

10.1	Introduction .....	171
10.2	Pig Iron .....	171
10.3	Cast Iron.....	172
10.4	Wrought Iron.....	175
10.5	Steel.....	176
10.6	Special Alloys Steels .....	179
	<i>Objective Brain Teasers</i> .....	182

## Chapter 11

### **Non-Ferrous Metals and Alloys ..... 186**

11.1	Introduction .....	186
11.2	Aluminium .....	187
11.3	Aluminium Alloys .....	188

11.4	Copper.....	189
11.5	Lead.....	193
11.6	Tin .....	193
11.7	Nickel .....	194
11.8	Magnesium.....	194
11.9	Titanium.....	194
11.10	Tungsten.....	195
11.11	Some Special Alloys.....	195
11.12	Babbitt Metals.....	196
11.13	Solder Material .....	196
11.14	Refractory Materials .....	196
11.15	Super Alloys.....	197
	<i>Objective Brain Teasers</i> .....	199

## Chapter 12

### **Introduction to Nanomaterial and**

### **Metamaterial ..... 203**

12.1	Nano Technology .....	203
12.2	Meta Materials .....	205
	<i>Objective Brain Teasers</i> .....	206

## Chapter 13

### **Basics of Corrosion and Creep ..... 208**

13.1	Corrosion .....	208
13.2	Self Potential .....	208
13.3	Polarization.....	208
13.4	Oxidizing Power Vs Corrosion Rate .....	209
13.5	Types of Corrosion .....	209
13.6	Corrosion Penetration Rate (CPR).....	210
13.7	Creep Curve.....	211
13.8	Recovery, Recrystallisation and Grain Growth.....	211
13.9	Difference between hot working and cold working .....	212
13.10	Strengthening Mechanisms of Materials .....	212
13.11	Hot Shortness or Sulphur-Embrittlement.....	213
	<i>Objective Brain Teasers</i> .....	214



## 2.1 Basic Laws of Chemistry

### Atomic mass unit

- It is defined as a mass exactly equal to one-twelfth the mass of one carbon - 12 atom.

$$1 \text{ amu} = 1.66056 \times 10^{-24} \text{g}$$

### Mole

- The mole is unit of measurement for mass of substance in the International System of Units (SI).
- "One mole is the amount of a substance that contains as many particles or entities as there are atoms in exactly 12 g (or 0.012 kg) of the  $^{12}\text{C}$  isotope".

$$1 \text{ mole} = 6.023 \times 10^{23} \text{ atoms}$$

- The mass of one mole of a substance in grams is called molar mass.

### Avogadro number

- In 1811, Avogadro proposed that equal volumes of gases at the same temperature and pressure should contain equal number of molecules. The number of entities or atoms in a mole is termed as Avogadro number, denoted by  $N_A$ .

$$N_A = 6.023 \times 10^{23} \text{ atoms/mol}$$

### Law of conservation of mass

Antoine Lavoisier in 1789 stated that:

- "Matter can neither be created nor destroyed by chemical reactions or physical transformations."
- He performed careful experimental studies for combustion reactions for reaching to the above conclusion.
- According to this in a closed system for chemical reaction, the mass of the products must be equal to the mass of the reactants.

### Law of Definite Proportions

A French chemist, Joseph Proust stated that:

- "A given compound always consist exactly the fixed and same proportion of elements by mass." It is sometimes also referred as Law of definite composition.
- An example is  $\text{CO}_2$ . This gas is produced from a variety of reactions, often by the burning of materials, wood or fossil fuels. The structure of the gas always consists of one atom of carbon and two atoms of oxygen.

### Law of Multiple Proportions

John Dalton proposed this law in 1803, he states that:

- When two elements combine to form more than one compound, the mass of one element that combines with a fixed mass of the other element, will always be in a ratio of whole numbers.

**Example:** Hydrogen combines with oxygen to form two compounds, named as water and hydrogen peroxide.

Hydrogen (2g) + Oxygen (16g)  $\rightarrow$  Water (18g)

Hydrogen (2g) + Oxygen (32g)  $\rightarrow$  Hydrogen Peroxide (34g)

Here, the masses of oxygen (16 g and 32 g) which combine with a fixed mass of hydrogen (2g) bear a simple ratio, i.e. 16:32 or 1:2.

## 2.2 Fundamental Concepts

- A substance which can not be decomposed into other substances is known as element. The smaller particle of an element which takes part in chemical reaction is known as an atom.
- An atom consists of a very small nucleus at its centre which is composed of protons and neutrons. The nucleus is encircled by moving electrons.
- The electron is a negatively charged particle and it has mass of about  $1/1836$  that of the neutron. Proton has positive charge while a neutron is an uncharged particle having mass equal to the proton.
- Each chemical element is characterized by the number of protons in the nucleus or the **atomic number (Z)**. For an electrically neutral or complete atom, the atomic number also equals the number of electrons.
- The **atomic mass (A)** of a specific atom may be expressed as the sum of the masses of protons and neutrons within the nucleus.
- The atomic weight of an element corresponds to the weighted average of the atomic masses of the atom's naturally occurring isotopes. The **atomic mass unit (amu)** may be used for computations of atomic weight.

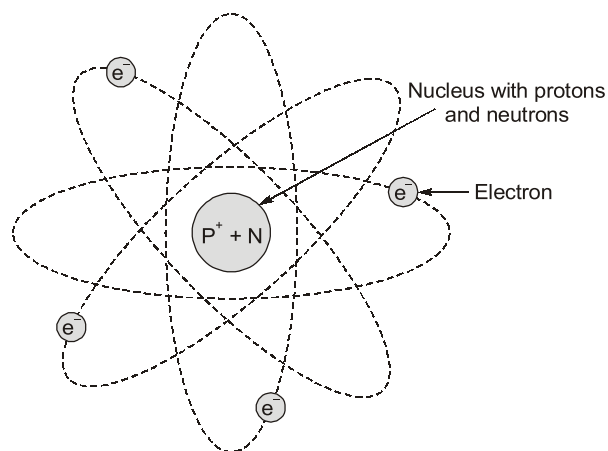


Fig. 2.1 Concept of an atom

### NOTE



A scale has been established whereby 1 amu is defined as  $1/12$  of the atomic mass of the most common isotope of carbon, (carbon -12,  $A = 12.00000$ ). Within this scheme, the masses of protons and neutrons are slightly greater than unity and

$$A \cong Z + N$$

where  $N$  = Number of neutrons.

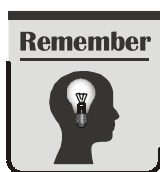
- **Isotopes:** Isotopes have different atomic weights but they have same atomic number. Isotopes are chemically inseparable as they possess identical chemical properties. Isotopes of the same element have the same atomic number and the same charge on the nucleus.  ${}_1\text{H}^1$ ,  ${}_1\text{H}^2$  and  ${}_1\text{H}^3$  are isotopes of hydrogen while  ${}_{17}\text{Cl}^{37}$  and  ${}_{17}\text{Cl}^{35}$  are isotopes of chlorine.
- **Isobars:** Atoms which have same mass number (atomic weight or number of protons and neutrons) but they differ in atomic number are called isobars. Isobars are atoms of different chemical elements but they have same atomic mass number.  $\text{Ar}^{40}$  and  $\text{Ca}^{40}$  are isobars having same atomic mass number of 40 but they have varying number of protons (atomic number) and neutrons.



- **Isotones:** Atoms whose nuclei have the same number of neutrons but different number of protons. Thus, chlorine-37 and potassium-39 are isotones as their nuclei contain 17 and 19 protons respectively but same 20 neutrons. Isotones have different atomic number and different chemical properties.

## 2.3 Electrons in Atoms

- The electrons, protons and neutrons in atoms of various elements are identical. Thus, it follows that electrons, protons and neutrons are the fundamental particles of the universe. If it is so, then why do various elements behave differently? This is because of the difference in the number and arrangement of the electrons, protons and neutrons of which each atom is composed.
- All the electrons of an atom do not move in the same orbit. The electrons in an atom are arranged in different orbits or shells.



### Remember

In general a shell (or orbit) can contain a maximum of  $2n^2$  electrons, where  $n$  is the number of shell (or orbit). But according to this rule, there is an exception, the outermost orbit in an atom can not accommodate more than eight electrons. The electrons present in the outermost shell (or orbit) are called valence electrons.

- All the elements have been arranged in a periodic table according to the electronic arrangements in their atoms. The element placed in one vertical column have very similar properties.

## 2.4 The Periodic Table

- All the elements have been classified according to electron configuration in the **periodic table**. Here, the elements are situated, with increasing atomic number, in seven horizontal rows called periods.
- The arrangement is such that all elements arrayed in a given column or group have similar valence electron structures, as well as chemical and physical properties. These properties change gradually, moving horizontally across each period and vertically down each column.
- The elements positioned in Group 0, the rightmost group, are the inert gases, which have filled electron shells and stable electron configurations. Group VIIA and VIA elements are one and two electrons deficient, respectively, from having stable structures.
- The Group VIIA elements (F, Cl, Br, I and At) are sometimes termed the halogens. The alkali and the alkaline earth metals (Li, Na, K, Be, Mg, Ca etc.) are labeled as Groups IA and IIA, having, respectively, one and two electrons in excess of stable structures.
- The elements in the three long periods, Groups IIIB through IIB, are termed as the transition metals, which have partially filled  $d$  electron states and in some cases one or two electrons in the next higher energy shell.
- Groups IIIA, IVA and VA (B, Si, Ge, As etc.) display characteristics that are intermediate between the metals and nonmetals by virtue of their valence electron structures.
- As may be noted from the periodic table, most of the elements really come under the metal classification. These are sometimes termed **electropositive** elements, indicating that they are capable of giving up their few valence electrons to become positively charged ions.
- Furthermore, the elements situated on the right-hand side of the table are **electronegative**; that is, they readily accept electrons to form negatively charged ions or sometimes they share electrons with other atoms.
- Atoms are more likely to accept electrons if their outer shells are almost full and if they are less “shielded” from (i.e., closer to) the nucleus.

**Fig. 2.2** The periodic table of the elements. The numbers in parentheses are the atomic weights of the most stable or common isotopes.

- The waves arising from the high-frequency end of the electromagnetic spectrum that has no mass are known as gamma rays.
- They hold the highest power of penetration. They are the most penetrating but least ionizing and very difficult to resist them from entering the body.
- The Gamma rays carry a large amount of energy and can also travel via thick concrete and thin lead.

## 2.5.4 Properties of Alpha, Beta and Gamma rays

Table 2.1 Characteristics of Alpha, Beta and Gamma Rays

Characteristic	Alpha ( $\alpha$ )	Beta ( $\beta$ )	Gamma ( $\gamma$ )
Emission of	$2P + 2N$	1 electron – High K.E.	Photon - very high frequency electromagnetic radiation
Changes from	Uranium to Plutonium	Radium to Polonium	No change
Charge (C)	+2	-1	0
Mass (amu)	4	1/1850	0
Speed km/s	15000	300000	300000
% of speed of light	5%	Close to 100%	100%
K.E.	3-6 MeV	5 MeV to 1 MeV	100 keV less than 10 MeV
Penetration Power	Low - Large mass & charge -can be stopped by a thin sheet of paper	Moderate - Medium mass and charge- can be stopped by a few mm thick metal	Very high - no mass, no charge, can be stopped only by a very thick cement or steel block
Ionization power	Very high - Large charge	Moderate - Low charge	Low - No charge

## 2.6 Quantum Number

Quantum numbers are used to find the electron configuration of an atom and the probable location, energy level, other characteristics like ionization and atomic radius of an electron in the atom. Quantum numbers are also applied to check the movement and orbit of each and every electron within an atom. Quantum numbers are of four types:

### 2.6.1 The principal quantum number ( $n$ )

- Principal quantum number of any electron in an atom stands for the main energy level or shell to which an electron belongs. Energy of an electron and its average distance from nucleus depends upon principal quantum number. Increasing the value of ' $n$ ' results the distance of electron from its nucleus and its energy also start increasing.
- Shells are specified by a principal quantum number  $n$ , which may require an integral values beginning with unity; sometimes these shells are designated by the letters  $K, L, M, N, O$  and so on, which correspond, respectively to  $n = 1, 2, 3, 4, 5, \dots$ , shown in Table 2.2.

Table 2.2 Electron states in some of electron shells & subshells

Principal quantum Number ( $n$ )	Shell Designation	Subshells	No. of States	Number of Electrons	
				Per Subshell	Per Shell
1	$K$	$s$	1	2	2
2	$L$	$s$	1	2	8
		$p$	3	6	
3	$M$	$s$	1	2	18
		$p$	3	6	
		$d$	5	10	
4	$N$	$s$	1	2	32
		$p$	3	6	
		$d$	5	10	
		$f$	7	14	

### 2.6.2 The orbital angular momentum/ azimuthal quantum number ( $l$ ):

$l$  is the second quantum number which represents the sub-shell, denoted by letters  $s, p, d$  or  $f$ ; it is related to the shape of the sub-shell of electron. The number of these sub-shells is defined by the magnitude of  $n$ . It specifies the number of units of angular momentum connected with an electron in a given orbit and finds the shape of the orbit and the energy of the sublevel.

**Note:** For any value of  $n$  quantum number  $l$  can have any integral value from 0 to  $n - 1$ . Hence we can have  $4d$ ,  $5f$ ,  $2p$  and  $2s$  electrons whereas  $1p$ ,  $2d$ ,  $3f$  subshell electrons do not exist.

**Example:** For

$$n = 1, \quad l = 0$$

$$n = 2, \quad l = 0, 1$$

$$n = 3, \quad l = 0, 1, 2$$

We have observed that  $n$  is the principal quantum number that defines principal shell.  $l$  provides the possible orbital sub-shells. The sub-shells in the main shell are  $s$ ,  $p$ ,  $d$ ,  $f$ ,  $g$  and  $h$  with quantum number  $l = 0, 1, 2, 3, 4$  and  $5$  respectively. We can demonstrate it as follows:

For  $n = 1, l = 0$ , the electron is said to be in  $1s$  sub-shell

$n = 2, l = 1$ , the electron is said to be in  $2p$  sub-shell

$n = 2, l = 0$ , the electron is said to be in  $2s$  sub-shell

### 2.6.3 The magnetic quantum number ( $m_l$ )

The third quantum number  $m_l$  is used to determine the number of orbitals for each subshell. For an 's' subshell, there is a single energy state, whereas for  $p$ ,  $d$  and  $f$  subshells three, five and seven states exist, respectively (Table 2.2).

- The value of  $m_l$  varies between  $+l$  to  $-l$  with zero and as we know that  $m_l$  have  $(2l + 1)$  values for a given  $l$ . For any specific value of  $l$ , an electron may have integral values of its inner quantum number  $m_l$  from  $+l$  through 0 to  $-l$ . Thus for  $l = 2$ ,  $m_l$  can take on the values  $+2, +1, 0, -1$  and  $-2$ . Thus we get

$$\text{For } l = 0, \quad m_l = 0$$

$$l = 1, \quad m_l = -1, 0, 1$$

$$l = 2, \quad m_l = -2, -1, 0, +1, +2$$

### 2.6.4 The Magnetic Spin Quantum Number ( $m_s$ )

- The electron can spin either in the clockwise or anticlockwise direction and values of spin can be  $+\frac{1}{2}$  and  $-\frac{1}{2}$ , depending upon the direction of spin.  $m_s$  is used to represent the spin of an electron.
- We need to remember that the three quantum numbers  $n$ ,  $l$  and  $m_l$  can have the same values for two electrons in an atom and that these two electrons will have their spins oriented in opposite directions.

#### Example 1.

Write the four quantum numbers for each of the electrons in the outermost shell of a boron atom?

**Solution:**

For boron,  $Z = 5$ , obviously, it has 5 electrons in it. Out of these 2 are in  $K$  shell and remaining 3 in the  $L$ -shell of the 3 electrons in the  $L$  shell 2 are  $2s$  electrons and 1 is a  $p$  electron. Hence the quantum numbers of the electrons in the  $L$ -shell are as follows:

$n$	$l$	$m_l$	$m_s$
2	0	0	$+\frac{1}{2}$
2	0	0	$-\frac{1}{2}$
2	1	0	$\pm\frac{1}{2}$

**Example 2.**

When the quantum number  $l = 4$ , the quantum number  $m_l$  takes the following number of values.

- (a) 8 (b) 10  
(c) 9 (d) 5

Ans: (c)

$$m_l = (2l + 1) = 2 \times 4 + 1 = 9$$

## 2.7 Electron Affinity

- This is the amount of energy released, when an electron is added by a neutral atom.
- The energy required to transfer an electron from one atom to another atom is the difference between the ionization energy  $I_1$  and the electronic affinity  $E_{12}$  of the respective atoms,  $I_1 - E_{12}$ .
- Chlorine has the highest electron affinity.

**NOTE**

1. Electron affinity decreases with increase in atomic radius.
2. Sign given to electron affinity is negative because energy is released.
3. When force of attraction decreases electron affinity decreases.

## 2.8 Electronegativity

- Electronegativity is a chemical property that defines the tendency of an atom to attract a bonding pair of electrons towards itself. When an element strongly attracts electrons then it means that element has high electronegativity.
- Electronegativity is a measure of the ability of an atom in a chemical compound to attract shared electrons to it.
- The higher the associated electronegativity number, the more an element or compound attracts electrons towards it.
- The electronegativity of any given element varies depending on the element to which it is bound.
- Caesium is the least electronegative element in the periodic table ( $= 0.79$ ), while fluorine is most electronegative ( $= 3.98$ ). Electro-positivity is opposite of electronegativity that is a measure of an element's ability to donate electrons.

## 2.9 Pauli's Exclusion Principle

He stated that, "No two electrons within the same atom can have the same numerical values for their set of four quantum numbers." This principle states that each electron state can hold no more than two electrons, which must have opposite spins. Thus,  $s$ ,  $p$ ,  $d$  and  $f$  sub-shells may each accommodate a total of 2, 6, 10 and 14 electrons respectively.

- Two electrons in an atom cannot be in the same quantum state i.e., their quantum numbers must be different.
- Of the four quantum numbers at least one must be different for the two electrons. For example  $n$ ,  $l$ ,  $m_l$  may be the same for the two electrons in an atom but the fourth quantum number  $m_s$  must be different for the two electrons. If  $m_s$  have  $+\frac{1}{2}$  for one electron then it must have  $-\frac{1}{2}$  for the other.
- Maximum number of electrons for a shell will be  $= 2n^2$  where  $n$  is the principal quantum number.

**Previous ESE Prelims Questions**

**Q.1** In the case of ionic bonding, the molecule is stable as long as the number of bonding electrons is

- (a) Equal to the number of antibonding electrons
- (b) Less than the number of antibonding electrons
- (c) Greater than the number of antibonding electrons
- (d) Equal to the number of antibonding neutrons

[ESE Prelims : 2017]

**Ans. (c)**

For stable molecular structure, number of electrons in bonding molecular orbital must be greater than number of electrons in antibonding molecular orbital.

**Q.2** Consider the following characteristics with respect to Alpha particles:

- 1. They have large specific ionization values.
- 2. They dissipate their energy rather slowly.
- 3. They can penetrate the outer layer of human skin.
- 4. Their emitters are heavy elements.

Which of the above statements are correct?

- (a) 1 and 4 only
- (b) 1 and 3 only
- (c) 2 and 4 only
- (d) 2 and 3 only

[ESE Prelims : 2018]

**Ans. (a)**

Alpha particles can not penetrate human skin. Emitters of  $\alpha$ -particles are heavy elements and they have large ionization power.

**Q.3 Statement (I) :** Atoms can neither be created nor destroyed.

**Statement (II) :** Under similar conditions of temperature and pressure, equal volumes of gases do not contain an equal number of atoms.

- (a) Both Statement (I) and Statement (II) are individually true and Statement (II) is the correct explanation of Statement (I)
- (b) Both Statement (I) and Statement (II) are individually true, but Statement (II) is not the correct explanation of Statement (I)
- (c) Statement (I) is true, but Statement (II) is false
- (d) Statement (I) is false, but Statement (II) is true

[ESE Prelims : 2018]

**Ans. (c)**

Under similar conditions of temperature and pressure, equal volumes of gases contain an equal number of atoms.

**Q.4** In which one of the following types of bonds, the bond formation is by free moving electrons in an array of positive ions?

- (a) Homopolar bond
- (b) Electrostatic bond
- (c) Metallic bond
- (d) Covalent bond

[ESE Prelims : 2020]

**Ans. (c)**

Metallic bond is formed when atoms give up their electrons and become positive ions. So the bond is formed between free moving electrons and positive ions.

Q.5 Which of the following are the characteristics of covalent compounds?

1. They are mostly gases and liquids.
  2. They are usually electric insulators.
  3. They are directional in nature.
  4. They are insoluble in polar solvents like water but are soluble in non-polar solvents.
- (a) 1, 2 and 3 only  
(b) 1, 2 and 4 only  
(c) 1, 3 and 4 only  
(d) 1, 2, 3 and 4

[ESE Prelims : 2020]

Ans. (d)

Q.6 Match the following:

- |                    |   |
|--------------------|---|
| I                  | II  |
| A. Thompson        | 1. The concept of converting mechanical work into heat          |
| B. James P. Joule  | 2. The theory of relativity                                     |
| C. Max Planck      | 3. The energy characteristics of light                          |
| D. Albert Einstein | 4. The energy equivalence between heat, work and electric power |
- Select the correct matching using the code given below:

- |     |   |   |   |   |
|-----|---|---|---|---|
|     | A | B | C | D |
| (a) | 3 | 4 | 1 | 2 |
| (b) | 1 | 4 | 3 | 2 |
| (c) | 3 | 2 | 1 | 4 |
| (d) | 1 | 2 | 3 | 4 |

[ESE Prelims : 2021]

Ans. (b)

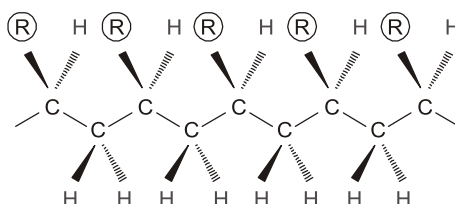
Q.7 Stereoisomerism denotes the situation in which atoms are linked together

- (a) in the different order and also differ in their spatial arrangement.
- (b) in the different order but same in their spatial arrangement.
- (c) in the same order (head-to-tail) but differ in their spatial arrangement.
- (d) in the same order (head-to-tail) and also same in their spatial arrangement.

[ESE Prelims : 2022]

Ans. (c)

**Stereoisomerism:** It denotes the situation in which atoms are linked together in the same order (head-to-tail) but differ in their spatial arrangement. For one stereoisomer, all the *R* groups are situated on the same side of the chain as follows:



### Objective Brain Teasers

Q.1 The bond between two identical non-metal atoms has a pair of electrons

- (a) with identical spins
- (b) unequally shared between the two
- (c) transferred fully from one to another
- (d) equally shared between them

Q.2 Which type of bonding would be expected between S and Cl?

- (a) ionic
- (b) non-polar covalent
- (c) polyionic
- (d) polar covalent